THE SENSITIVITY OF BARLEY, FIELD BEANS AND SUGAR BEET TO SOIL COMPACTION

by

Jeremy Charles Brereton, B.Sc.

Thesis submitted to the
University of Nottingham for the degree of
Doctor of Philosophy

January 1986

ABSTRACT

The sensitivity of spring barley (Hordeum vulgare, cv. Carnival), field beans (Vicia faba, cv. Maris Bead) and sugar beet (Beta vulgaris, cv. Monoire) to topsoil compaction induced by tractor wheelings, post sowing, on a coarse gravelly loam of the Arrow series was investigated in 1983 and 1984.

The study revealed that in both years topsoil compaction increased the dry bulk density, vane shear strength and cone resistance of the soil. Although compaction reduced only the plant population of sugar beet in 1983 (by 35%) in 1984 it both delayed emergence and decreased the field bean, spring barley and sugar beet populations by 41%, 50% and 64% respectively.

In 1983 the order of sensitivity of crop yield to soil compaction was spring barley $<$ field beans $<$ sugar beet and the following year a similar trend was apparent with spring barley $\approx$ field beans $<$ sugar beet. Compaction reduced the total dry matter production of field beans and sugar beet in 1983 and of all the three crops examined a year later. No clear trend could be established on the influence of soil compaction on plant nutrient uptake.

The total length and distribution of roots in the soil profile was reduced in field beans (28%), spring barley (27%) and sugar beet (49%) by topsoil compaction in 1983. However, the reduced root length of spring barley was an order of magnitude greater than that of the other crops. In 1984 there was a trend for compaction to restrict the total root length of all crops throughout most of the growing season. Compaction did not restrict the maximum depth of rooting but it reduced the amount of deep

roots in all crops. In 1983 and 1984, compaction restricted lateral proliferation of roots and the order of sensitivity of root distribution to soil compaction was similar to that for the sensitivity of yield : spring barley < field beans < sugar beet.

The maximum effective rooting depth, as measured by neutron probe, was consistently less for field bean and sugar beet compact treatments, while the evaporation was only reduced in compact sugar beet crops. Thermocouple psychrometer data indicated that compaction had generally delayed soil drying and reduced the extent of water use in all crops in 1984.

The principal effect of soil compaction on crop growth and dry matter production was to reduce the leaf area index, by an initial restriction to individual leaf size and by a reduction in plant numbers such that the fraction of light intercepted by the leaf canopy was reduced. The efficiency of conversion of photosynthetically active radiation absorbed to dry matter was not affected by soil compaction.

Diurnal and seasonal plant water status was not detrimentally changed by soil compaction. It is suggested that plants adapt to adverse soil physical conditions by a reduction of leaf area expansion rather than by lowered leaf water potential.

The severity of the response of crops to topsoil compaction was strongly influenced by the environment, in particular the distribution of rainfall which appeared to determine the effect of compaction on crop emergence and the ability of that crop to compensate for a low plant population.

The results of this study are discussed in relation to the use of plant breeding, irrigation and management techniques in overcoming the detrimental effects of soil compaction on crop growth and development.

ACKNOWLEDGEMENTS

I should like to express my gratitude to all those who have assisted me in the planning and execution of this project, namely Dr J.A. Roberts, Dr T.C.K. Dawkins and Dr M. McGowan.

I should like to acknowledge the large contribution made by Miss D. Hector, Mr S. Marshall, Mr J. Woods and Mr D. Leaper towards collection of the data from the 1984 field trial.

Thanks are also due to members of the Soil Science and Agronomy field unit staff and to Mr J. Craigon of the Biometry unit for many hours of statistical guidance.

I am indebted to Mr J. Whitehead for his most accurate work and care in the typing of this thesis.

I am most grateful to my parents for their constant encouragement and generous financial support throughout my academic career, and to my wife Lynda for all that she has given to me during the last three years.

This work was funded by a MAFF studentship.

CONTENTS

Chapter 4 CROP GROWTH

ABBREVIATIONS AND SYMBOLS

ABA	abscisic acid
ACC	1-aminocyclopropane-1-carboxylic acid
ADAS	Agricultural Development Advisory Service
Am	americium
AVG	aminoethoxy -vinyl glycine
Be	beryllium
Ca	calcium
cm	centimetre
cv	coefficient of variation
DF	degrees of freedom
DIHB	3,5 diiodohydroxybenzoic acid
EEC	European Economic Community
$\bar{\varepsilon}$	mean conversion efficiency
ε_m	maximum conversion efficiency
g	gramme
GA_3	gibberellic acid
GMT	Greenwich Mean Time
ha	hectare
hr	hour
IAA	Indole-3-acetic acid
K	potassium
kg	kilogramme
km	kilometre
kPa	kilopascal
kw	kilowatt
l	litre
LAI	Leaf Area Index
m	metre
µm	micrometre
mm	millimetre

Abbreviations and Symbols (continued)

mA	milliamp
mci	millicurie
mV	millivolt
MJ	megajoule
MPa	megapascal
MACC	malonyl 1-aminocyclopropane-1-carboxylic acid
MAFF	Ministry of Agriculture, Fisheries and Food
mc	moisture content
Mg	magnesium
Mn	manganese
N	Nitrogen
Na	Sodium
nm	nanometre
NS	non significant
P	phosphorus
$p<0.05$	probability is less than 0.05
PAR	photosynthetically active radiation
SE	standard error
SED	standard error of difference
t	tonne
USA	United States of America
USSR	Union of Soviet Socialist Republics
v/v	volume by volume
%	percent
90°	90 degrees
°C	degrees centigrade
ψ_g	gravitational potential
ψ_l	leaf water potential
ψ_π	osmotic potential
ψ_m	matric potential
ψ_p	turgor pressure

Note: Throughout this thesis plants from the compact treatment will be referred to as 'compact plants' or the 'compact crop'.

Chapter 1

INTRODUCTION

The yields of most crops are generally increasing as a result of advances in farm technology. However there is much concern about the contribution of modern farming practice to the incidence of soil compaction and to structural damage.

Soil compaction may be defined as the application of an external source which causes soil particles to slide over one another into a state of closer packing (Gooderham, 1977). Examination of the soil fabric can reveal a reduction in the number of macropores and a change in the shape and continuity of pores. This is reflected in changes in the 'packing state' of the soil. The associated increase in strength and the reduction in the conductivity, permeability and diffusivity of water and air through the soil pore system may have serious consequences in respect of plant growth (Soane, Blackwell, Dickson and Painter, 1981). Compaction is thus a complex process which involves inter-relationships between the physical, chemical and biological properties of soils and the environmental factors such as climate, weather and tillage (McKibben, 1971).

Contemporary crop production necessitates the passage of wheeled vehicles for the purpose of cultivation, sowing, spraying and harvesting. Up to 90% of the soil surface may be covered by tractor wheelings when a seedbed is prepared (Soane, 1970). Voorhees (1977) found that for six operations in the planting of maize, a tractor's dual wheels covered the entire field approximately twice.

The trend towards larger farm units and the high cost of farm labour have resulted in a significant increase in the power and weight of agricultural machinery. The average gross weight of tractors has increased from 2.7 t in 1948 to 4.5 t in 1968, while their average power has increased by approximately 6-7% per annum since 1970 (McKibben, 1971). The average power of tractors in the USSR and in the USA increased by approximately 30% between 1965 and 1975, while in the former country 200 kW tractors are now made freely available by mass production (Dvortsov and Polyak, 1979). Tractors however are not the heaviest vehicles to pass over farm soils. Machinery used for transporting and spreading slurry may exceed 20 t gross.

During secondary cultivation and sowing, the soil strength is low owing to the loosening received during primary cultivation while the soil itself is generally moist at that time of year. In such conditions, tractors can cause appreciable compaction. Ljungars (1977) reported that the frequency of wheel passes and the soil water content were the principal factors responsible for the compaction caused by seedbed traffic. When soils are dry and of high strength (for example, during the cereal harvest in Southern and Eastern Europe), field machinery may not result in substantial compaction problems. However, the weather conditions during the cereal harvest in Northern Europe are often unpredictable and the date of the return of the soil to field capacity is often early so that compaction caused by harvest traffic may occur to a depth of 15 cm (Pidgeon and Soane, 1978).

The problem of soil compaction is particularly serious if a crop, such as sugar beet, has to be harvested in late autumn when the land is too wet and when evaporation is very low (Plate 1.1).

Plate 1.1 Harvesting of sugar beet in late autumn when the land is wet can result in severe soil compaction

Another important factor is that the present large size of farm units make greater demands upon tractor power and in consequence it is more difficult to ensure timely cultivation (Gooderham, 1973). For this reason some of the most fertile and highly priced land in Britain is becoming increasingly difficult to work during those years when the rainfall is high (Russell, 1971).

As a result of advanced farming techniques there is a tendency for intensive arable production to become separated from pasture and livestock production. This factor, and the significantly greater use of chemical fertilizers have resulted in a reduction in the quantity of farmyard manure applied to arable land. The organic matter content has an important influence on the compactability of soils. Soane (1970) found that the greater the organic matter content, the lower was the maximum bulk density and the higher was the optimum moisture content for maximum bulk density. Free, Lamb and Carleton (1947) reported that a reduction in the organic matter content of a silt loam from 4.1% to 2.5% resulted in an increased bulk density from 1.4 g cm^{-3} to 1.6 g cm^{-3}.

The harmful effects of compact soil on crop production have been known for many hundreds of years. Indeed, Virgil (70-19 BC) described a method for determining soil bulk density and observed that "loose soils provide bounteous vines but dense soils provide reluctant clods and stiff ridges".

More recently, Trouse and Humbert (1961) recorded a reduction in the yield of sugar cane from 218 t ha^{-1} to 148 t ha^{-1} owing to the compacting effect of the mechanical harvester. This was attributed to either a reduction in the volume of soil explored by the root system or to the impaired absorbing capacity of the roots.

Phillips and Kirkham (1962) found that compaction, produced by predrilling wheelings, reduced the plant population and growth in a maize crop, which resulted in reduced yields. This was attributed to the mechanical impedance of root growth, since the grain yield was found to be directly proportional to the weight of roots in a 60 cm layer of soil.

Fisher, Gooderham and Ingram (1975) investigated the effect of poor soil physical conditions, caused by 'wet' ploughing, on the yield of kale and spring barley. The yield reduction, due to compaction, was greater in the kale than in the barley and this was thought to be a result of an initial retardation of root growth and consequent poor nutrient uptake.

Hebblethwaite and McGowan (1980) suggested that the effect of compaction on sugar beet yield could be attributed to poor root development which prevented the full use of soil water and nutrient reserves.

Some researchers have implied that poor soil aeration is a causal agent in reducing crop yields in compact soil (Baver and Farnsworth, 1940). However, it is unlikely to cause a significant inhibition of plant growth because the root systems of many species are unlikely to suffer from shortage of oxygen unless large volumes of the surrounding soil are almost oxygen free (Greenwood, 1969).

Yield reductions, related to poor aeration, may occur if compaction causes waterlogging of the soil surface owing to poor infiltration of rain water. The consequences include accumulation of metabolically generated gases (ethylene) and the products of potentially toxic substances which may inhibit plant growth.

Since soil compaction was thought to invoke a yield reduction mainly by physically impeding root growth, a considerable amount of

attention has been directed towards the response of roots to mechanical impedance (Barley, 1965; Goss, 1977; Wilson and Robards, 1979). This work has generally been performed in controlled environmental conditions in the laboratory and a synthetic growth medium has been employed. While the value of such work should not be underestimated, the extrapolation of the results to crop growth in a field situation, with the complexity of soil structure and a widely varying soil water status, should be made with caution. Indeed there is evidence in the field that poor root growth in one part of the soil profile may be compensated for by increased root activity elsewhere (Soane, Dickson and Campbell, 1982).

This thesis reports the findings of a Ministry of Agriculture, Fisheries and Food Studentship which was awarded in 1982 for the further study of the effects of soil compaction on plant growth. After extensive literature research had been performed it was considered that three very important aspects of this subject had previously been neglected or inadequately investigated by other researchers:

1.1 The Sensitivity of Different Crops to Soil Compaction

Although many workers have reported the sensitivity of different crops to soil compaction (Batey and Davies, 1971; Davies, 1975; Wilkinson, 1975; Swain, 1981), few studies have involved a direct comparison of different crop species, grown in the same soil and under the same climatic conditions.

The response of different crops to soil compaction was reported by Batey and Davies (1971) (Table 1.1). The data was taken from case histories of typical problems investigated by Soil Science Advisors and since it represents a range of conditions encountered in the field, where

Table 1.1 The yield of crops grown in adverse soil conditions

Crop	Location	Soil Type	Yield (t ha^{-1}) Normal	Poor	% Yield Reduction
Potato	Lincolnshire	Silt loam over peat	26.2	11.2	57
Winter wheat	Northamptonshire	Loamy sand over sand	5.2	2.3	55
Sugar beet	Lincolnshire	Silt clay loam over Fen clay	40.0	17.0	57
Sugar beet	Shropshire	Deep sandy loam	33.6	19.8	41
Sugar beet	Shropshire	Loamy sand	46.4	23.2	50
Peas	Lincolnshire	Very fine sandy loam	2.6	0.9	67
Onions	Cambridgeshire	Loamy peat over Fen clay	31.0	22.2	29
Spring barley	Bedfordshire	Fine sandy loam over chalk	3.1	1.5	52
Spring oats	Staffordshire	Sandy loam	3.6	1.2	66

(Batey and Davies, 1971)

crops had been affected by soil structural defects, the terminology of Table 1.1 is necessarily vague. The work reports on several different sites and although the yield reductions gave some indication of the sensitivity of crop yield to compaction, variations in the degree and depth of compaction, in the season, in the time of sowing and in the soil type, reduced the validity of making a direct comparison between the crops.

The identification of the sensitivity of different crop species to soil compaction, when grown in the same soil and under the same climatic conditions was considered to be the principal objective of this study because it would yield practical information of immediate value to the grower. Given this type of information he could select the crop to give the best yield on land which may be prone to soil compaction. It was also hoped that by comparing the response of three different species to compaction, it may be possible to elucidate some of the mechanisms by which crop yield is reduced.

Spring crops are more susceptible to problems of soil compaction than winter crops owing to the short time span between emergence and the onset of possible drought conditions, which can make large demands on an already restricted root system, in early summer. Field beans, spring barley and sugar beet were chosen to represent a dicotyledonous species, a monocotyledonous species and a dicotyledonous species with the root being of major agricultural importance, respectively. Each crop demonstrated a sensitivity to poor soil conditions in a laboratory test which preceded the field trials at the School of Agriculture, Sutton Bonington.

The total area of field beans grown in England and Wales has declined over the last 10 years. As a consequence of limited improvement in crop yield and comparatively low farm prices there was a 40% reduction in gross margins between 1973 and 1979 (Waterer, 1981).

Although the field bean crop is a good break crop giving residual nitrogen to the soil, it matures late and the physical yields and financial returns are notoriously variable. However, the field bean has historically been regarded as a crop of low inputs and it has been suggested that higher inputs could consistently increase yields (McEwen, 1982). It is possible that field beans could regain their popularity owing to an improvement in their market value, stimulated by the EEC Feed Protein Subsidy.

The total area of Barley grown has remained constant during the last 10 years owing primarily to the introduction of cheap fungicides for mildew control and to varietal improvement. This has allowed the crop to maintain its importance in comparison with wheat and oilseed rape.

Spring barley is a valuable rotation crop and it is usually sown after a late lifted root crop. It currently occupies 57% of the total area of barley grown in England and Wales, but it is more popular in Scotland where the variety Golden Promise comprises 90% of all the malting barley purchased.

Spring barley possesses a generally low susceptibility to disease while the long period from harvesting to drilling permits effective control of volunteer winter cereals and autumn germinating weeds. Disease carryover from crop residues is also reduced. It is believed that the area of spring barley grown may soon expand, the reason being that variable costs increase in relation to prices with a detrimental effect on high input winter cereal systems (Lobley, 1982).

In 1982, 9 million tonnes of sugar beet roots were grown on 203,000 ha, producing an average yield of 45 t ha^{-1} with an average sugar content of 16 per cent (Ministry of Agriculture, Fisheries and Food, 1983). Methods of sugar beet production have changed greatly during the last 30

years. Developments include the introduction of precision drills and mechanical harvesting equipment with increased variety performance, seed quality, herbicide development and disease and pest control (Sugar Beet Research and Education Committee, 1982a).

Although current trends do not wholly reflect these developments, the Gross Margin associated with sugar beet may be as great as £732 per hectare compared with £1057 per hectare for potatoes and £422 per hectare for oilseed rape (Sugar Beet Reasearch and Education Committee, 1982a). It is thus an important crop in the rotation.

The yield of the sugar beet crop is particularly sensitive to soil compaction because the crop is drilled to a stand and because of the wide seed spacing, the slightest reduction in plant population is reflected in a reduced yield.

1.2 The Effect of Soil Compaction on the Development of the Leaf Canopy and the Efficiency of Conversion of Solar Radiation to Dry Matter

The grain yield has been found to be linearly related to the final total dry weight of a crop (Biscoe, 1979; McLaren, 1981) while the total dry matter production is proportional to the amount of solar radiation absorbed by the foliage (Gallagher and Biscoe, 1978; Monteith and Elston, 1983). The dry matter produced by the crop will depend upon:

i) the quantity of the incident radiation from the sun,

ii) the fraction of radiation absorbed by the foliage and

iii) the 'efficiency' of the crop to convert dry matter from absorbed radiation.

A schematic diagram to show the factors affecting the production of the crop yield by the leaf canopy is presented in Figure 1.1.

In Northern Europe the production of dry matter is unlikely to be greatly influenced by the quantity of incident radiation, partly because leaves tend to be saturated with light in bright sunshine and partly because the amount of radiation received over a specific length of the growing season does not vary much between years (Monteith, 1981).

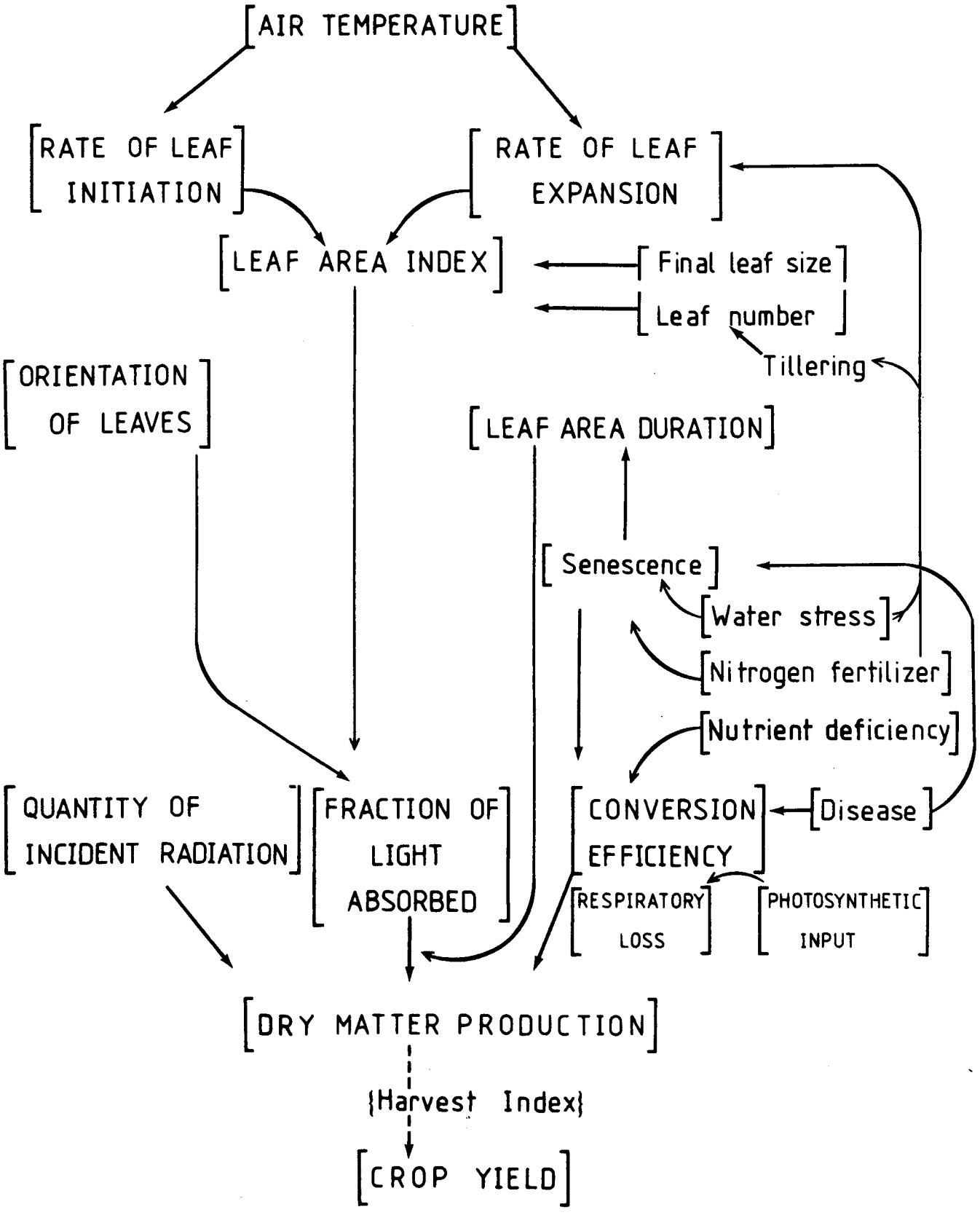
The major determinant of crop biomass production is thought to be the proportion of radiation intercepted (Green, 1984b). This fraction depends upon the size of the leaf canopy in relation to the ground area (Leaf Area Index) and the orientation of the leaves.

It is important that the leaf area is produced rapidly thus minimising wastage of light early in the growing season, owing to incomplete leaf canopy. The growth of the canopy is related to the rate of leaf initiation and expansion (Gallagher, 1979). These features are primarily determined by temperature but the rate of leaf area expansion may be restricted by poor mineral nutrition (Dennet, Auld and Elston, 1978) and water stress (Karamanos, 1978).

In cereals a leaf area index of between 4 and 5 is required to absorb 90% of the available radiation.

The leaf number of cereal crops is primarily dependent on tillering (Biscoe, 1979) and both water stress and nitrogen fertilizers can change the tillering habit and the final size of individual leaves (Biscoe and Gallagher, 1978) thus influencing the maximum size of the crop canopy. Soane, Dickson and Campbell (1982) found that soil compaction caused a 5% reduction in the maximum leaf cover of a sugar beet crop.

Figure 1.1 Schematic diagram to show the factors affecting the production of crop yield by the leaf canopy


AIR TEMPERATURE
RATE OF LEAF INITIATION
RATE OF LEAF EXPANSION
LEAF AREA INDEX
Final leaf size
Leaf number
Tillering
ORIENTATION OF LEAVES
LEAF AREA DURATION
Senescence
Water stress
Nitrogen fertilizer
Nutrient deficiency
QUANTITY OF INCIDENT RADIATION
FRACTION OF LIGHT ABSORBED
CONVERSION EFFICIENCY
Disease
RESPIRATORY LOSS
PHOTOSYNTHETIC INPUT
DRY MATTER PRODUCTION
{Harvest Index}
CROP YIELD

The time during which radiation can be absorbed is dependent on the persistence of the green canopy (Leaf Area Duration). This is related to the beginning of senescence which can be advanced by water stress (Lawlor, Day, Johnston, Legg and Parkinson, 1981), disease (Green and Ivins, 1984) and nutrient deficiency (Wareing and Phillips, 1970).

The 'conversion efficiency' of radiation into dry matter (here defined as the quantity of dry matter produced per unit of Photosynthetically Active Radiation (PAR) absorbed) represents a balance between photosynthetic input and respiratory loss (Green, 1984b). The fraction of carbon required is considered to be a constant fraction of the carbon fixed and therefore the conversion efficiency is related to the canopy photosynthetic rate (Biscoe and Gallagher, 1975).

There is conflicting evidence as to whether water stress reduces the conversion efficiency. Lawlor et al. (1981) found little response of the photosynthesis of barley to drought and they reported the principal effect to be a reduction in the canopy size and hence quantity of light absorbed. Hsiao and Acevedo (1974) also found that the conversion efficiency was largely unaffected by water stress, however Ison (1984) reported that water stress reduced the conversion efficiency of field beans.

Green (1984a) found that extreme nitrogen deficiency caused a reduction in the conversion efficiency of wheat, while Gallagher and Biscoe (1978) reported a decreased efficiency of droughted crops on nitrogen rich soil. They attributed this effect to a nitrogen induced increase in the canopy size with a concomitant increase in the demand for soil water.

Notwithstanding many years of research directed toward the problem of soil compaction, there is little information on the effects of compaction on the development of the leaf canopy and the efficiency of

conversion of solar radiation to dry matter. The identification of these effects was therefore considered to be a primary objective of this study.

1.3 The Effects of Soil Compaction on the Plant Water Status

Soil compaction is generally considered to influence plant growth by modifying the depth and distribution of the root system, thus preventing full use of soil water. It is probable that changes of this character would increase the susceptibility of a crop to water stress and thus reduce the final yield.

Leaf water potential has been used as an indicator of plant water deficit (Klepper and Barrs, 1968) and it has also been related to crop growth and yield (Hoffman and Hiler, 1972). Therefore a study of the plant water balance, as influenced by soil compaction, was considered to be an essential objective of this detailed study, in order to determine whether water stress is involved in the mechanisms by which soil compaction reduces crop yield.

To summarize therefore, the primary objectives of this research project were:

i) to evaluate the effects of soil compaction on the growth and development of field beans, spring barley and sugar beet and thus to identify the sensitivity of these crops to soil compaction.

ii) to investigate whether soil compaction influences the leaf canopy development of these crops and the efficiency with which they convert solar radiation to dry matter.

iii) to study the effects of soil compaction on the water status of field bean, spring barley and sugar beet plants and thereby elucidate the importance of water stress as the causal agent in the reduction of crop yields on compact soils.

Chapter 2

WEATHER AND EXPERIMENTAL DETAILS

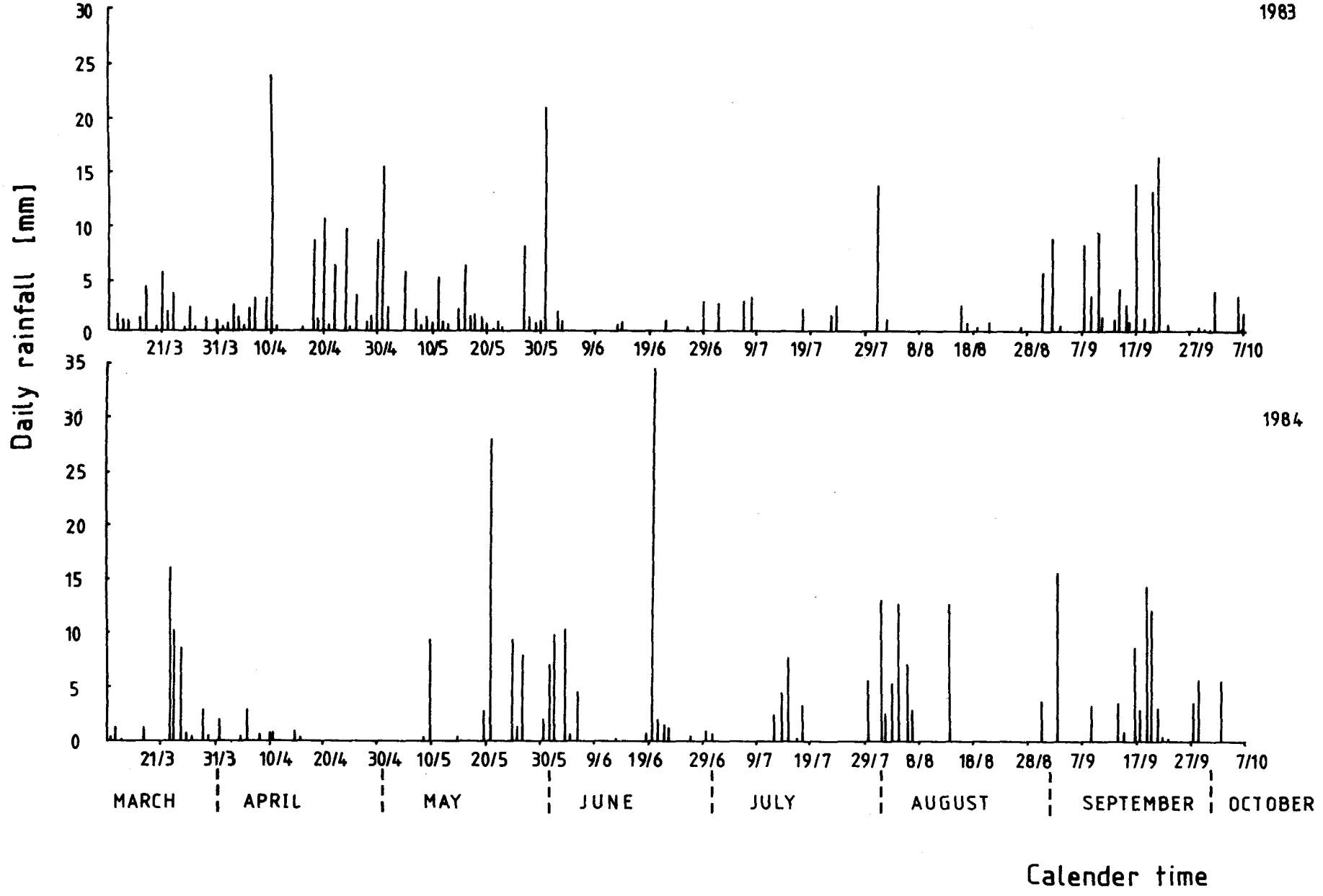
2.1 Geographical Location

The field trials were conducted on the experimental farm of the School of Agriculture, University of Nottingham, at Sutton Bonington. The 1983 trial was located in field 25 (Ordnance Survey, sheet 129, reference 507268) and the 1984 trial was located in field 26 (Ordnance Survey, sheet 129, reference 504270).

2.2 Weather

Weather data were recorded daily at the Sutton Bonington meteorological station, which is situated less than 1 km from the experimental sites. The distribution of rainfall in 1983 contrasted with that received in 1984 (Figure 2.1) and with the long term average (Figure 2.2(a)). In 1983 more rain was received during the crop emergence period (March and April) than was to be expected from the long term average data but in 1984 less than 10 mm of rain was received during April which was below the recorded average rainfall for that month. However, the rain received during June, July and August, 1983 was below the average but only in July, 1984 was the rainfall lower than the long term average for the summer months. These two contrasting seasons were eminently suitable for the study of topsoil compaction because the severity of the response is mainly governed by the soil moisture content at crop emergence (Dawkins, 1982).

Figure 2.1 The daily rainfall received throughout the 1983 and 1984 growing season


1983
1984
Daily rainfall [mm]
30
25
20
15
10
5
0
35
21/3
31/3
10/4
20/4
30/4
10/5
20/5
30/5
9/6
19/6
29/6
9/7
19/7
29/7
8/8
18/8
28/8
7/9
17/9
27/9
7/10
MARCH
APRIL
MAY
JUNE
JULY
AUGUST
SEPTEMBER
OCTOBER
Calender time

Figures 2.2(b) to (e) present the monthly mean values for solar radiation, maximum and minimum air temperature and soil temperature in both the years together with the corresponding long term average. The mean daily radiation was similar for both growing seasons (Figure 2.2(b)) as was expected because there is generally little variation in total irradiance between seasons (Monteith, 1977).

The maximum and minimum screen temperatures are shown in Figure 2.2(c) and (d) respectively. Temperatures were similar throughout the growing season but were higher in July 1983.

The monthly mean soil temperatures for 1983 and 1984, at 10 cm depth were similar at crop emergence and throughout both seasons. The higher air temperature in July 1983 was reflected in a higher topsoil temperature (Figure 2.2(e)).

2.3 Experimental Site Details

The trial was conducted, in 1983 and in 1984, on soil of the Arrow series (Thomasson, 1971), an imperfectly drained, coarse textured fluvio-glacial drift from Triassic deposits overlying Keuper Marl at about 1 m depth. A representative profile of the Arrow series soil is given in Figure 2.3. It is a soil type which does not readily recover from soil compaction (O'Sullivan and Ball, 1982b). Field capacity conditions are generally reached shortly after heavy rain, due to rapid profile drainage (Hebblethwaite and McGowan, 1977).

The 1984 trial was situated less than 0.5 km from the location of the 1983 trial site. Four crops were studied in 1983: field beans, spring barley, sugar beet and grass (Table 2.1). However, grass was not included in the 1984 trial because in 1983 it was found to be insensitive to the

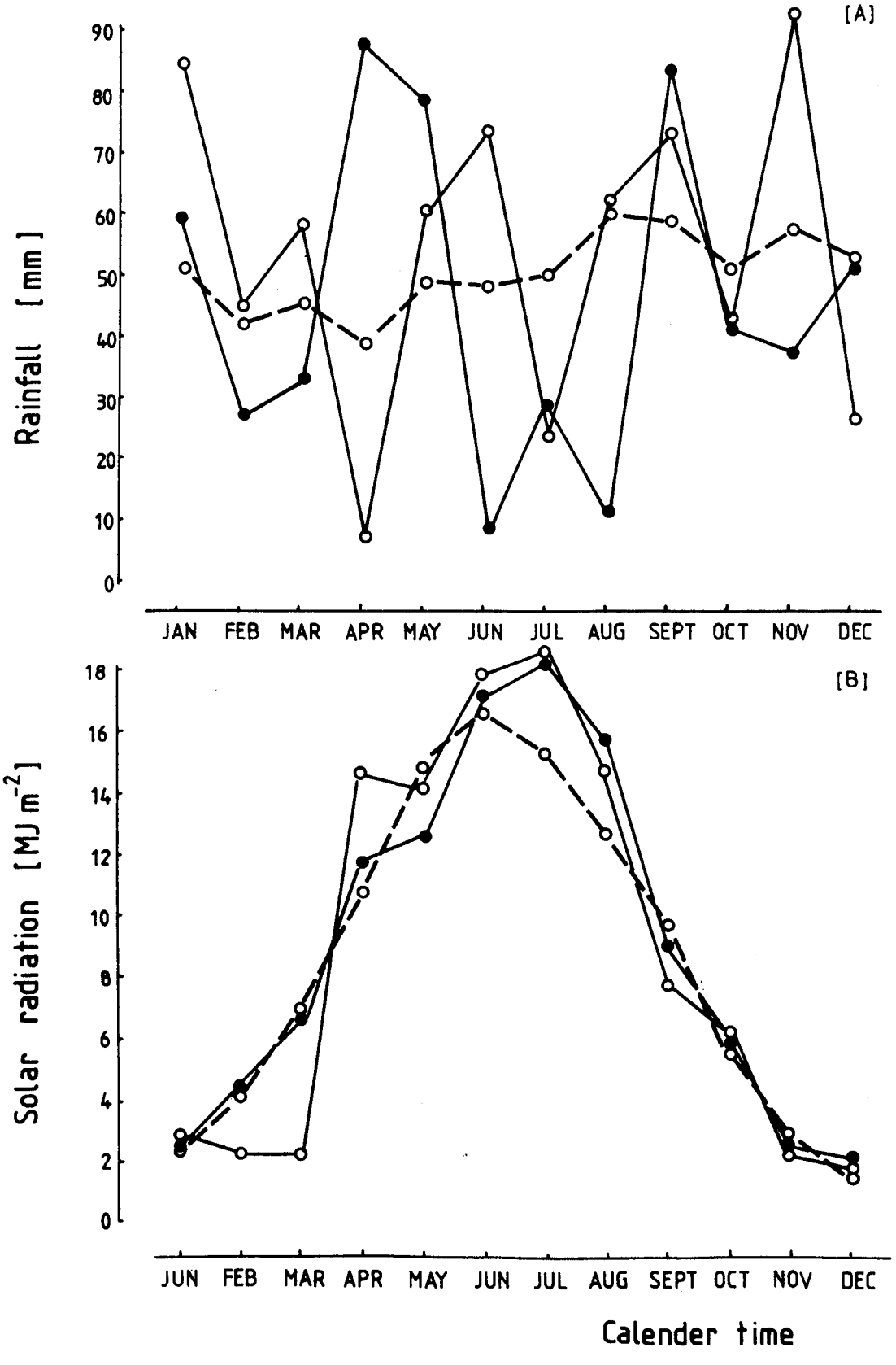
Figure 2.2 (a) Monthly mean rainfall for 1983 and 1984 with the long term average (1916-1984). 1983 (o—o); 1984 (●—●); Long term average (o--o)

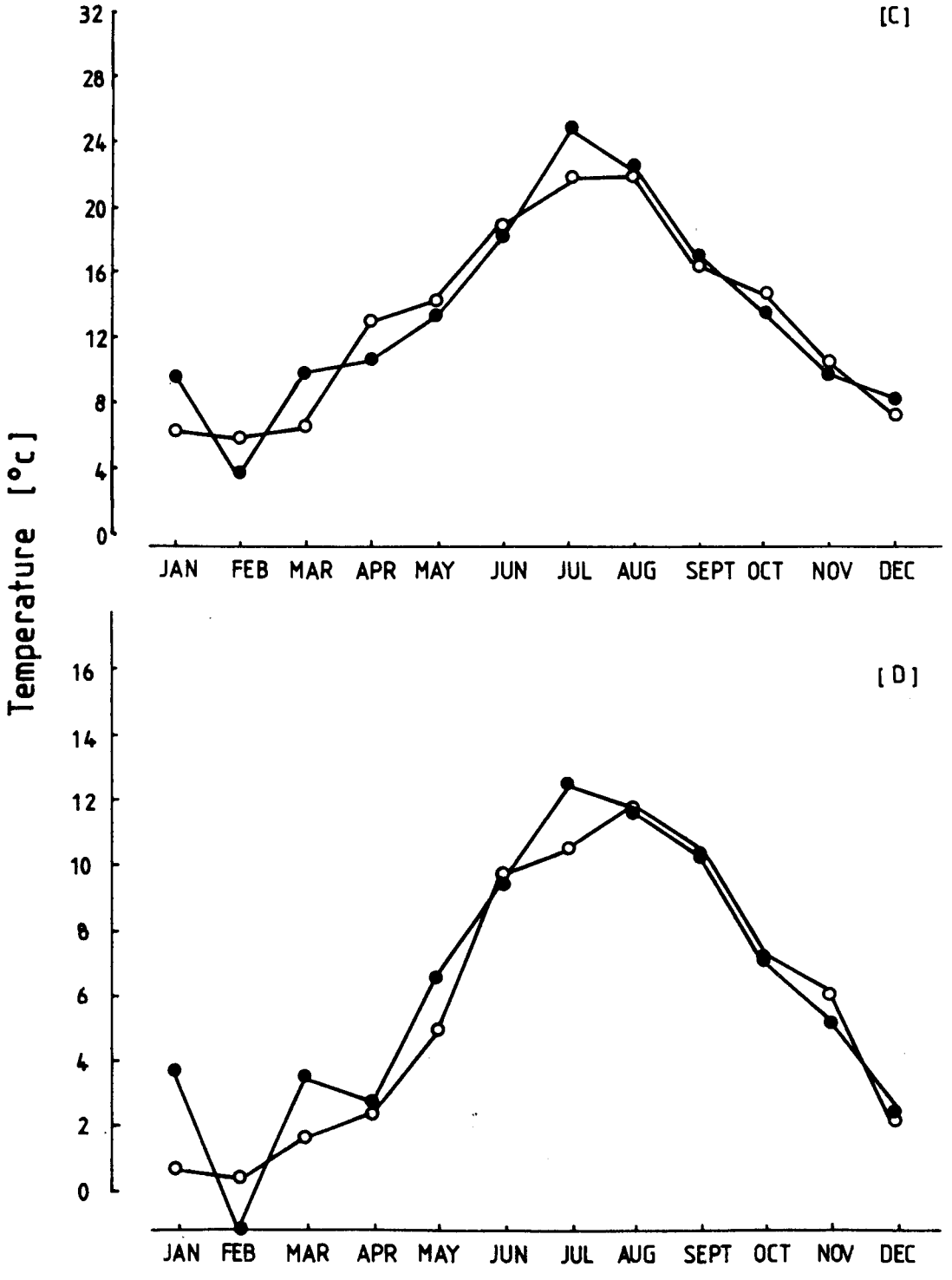
(b) Monthly mean solar radiation for 1983 and 1984 with the long term average (1958-1984). 1983 (o—o); 1984 (●—●); Long term average (o--o)

(c) Monthly mean maximum air temperature for 1983 and 1984. 1983 (o—o); 1984 (●—●)

(d) Monthly mean minimum air temperature for 1983 and 1984. 1983 (o—o); 1984 (●—●)

(e) Monthly mean soil temperature at 10 cm depth in 1983 and 1984 with the long term average (1946-1984). 1983 (o—o); 1984 (●—●); Long term average (o--o)


[A]
Rainfall [mm]
90
80
70
60
50
40
30
20
10
0
JAN FEB MAR APR MAY JUN JUL AUG SEPT OCT NOV DEC
[B]
Solar radiation [MJ m^{-2}]
18
16
14
12
10
8
6
4
2
0
JUN FEB MAR APR MAY JUN JUL AUG SEPT OCT NOV DEC
Calender time


[C]
32
28
24
20
16
12
8
4
0
JAN FEB MAR APR MAY JUN JUL AUG SEPT OCT NOV DEC
[D]
16
14
12
10
8
6
4
2
0
JAN FEB MAR APR MAY JUN JUL AUG SEPT OCT NOV DEC
Temperature [°C]
Calender time

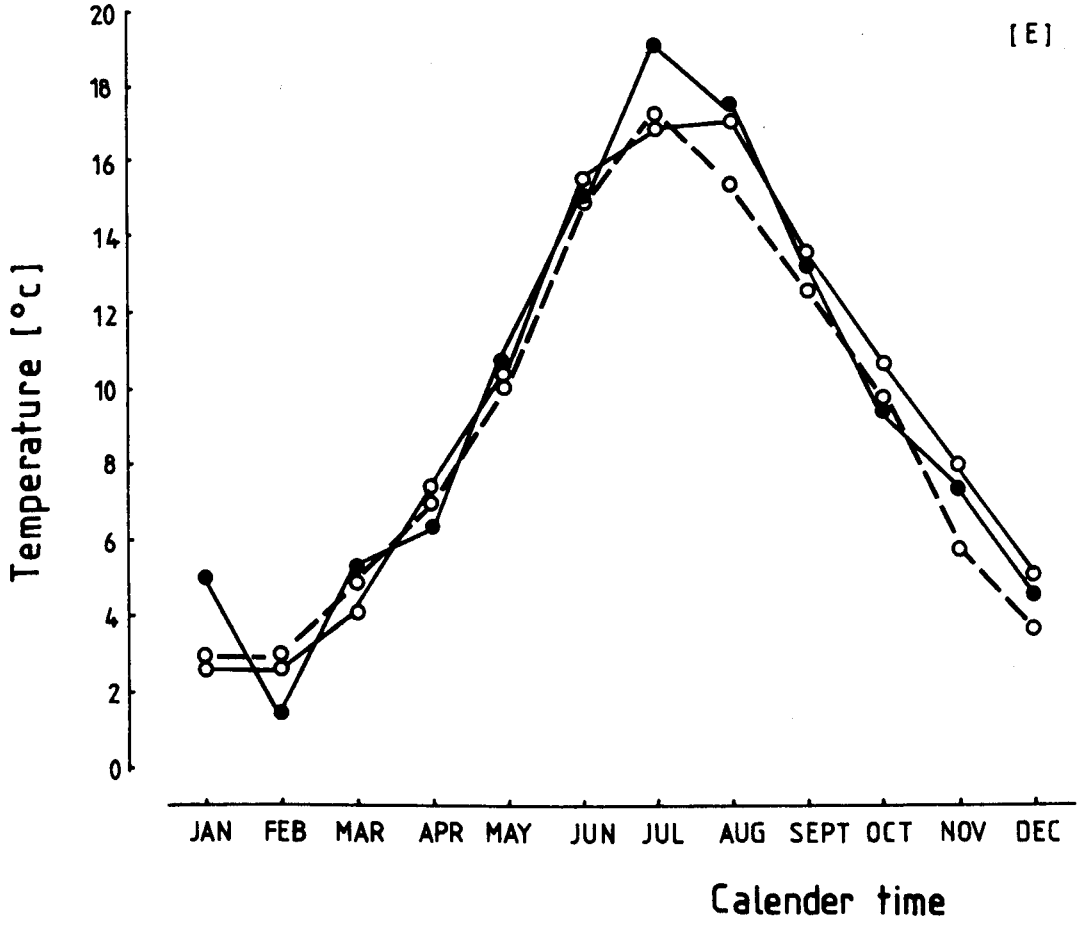
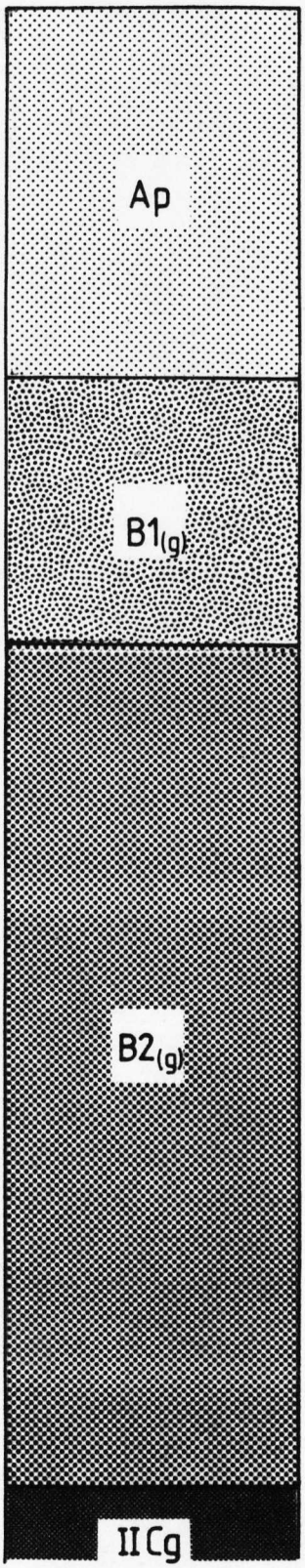

[E]
Temperature [°c]
20
18
16
14
12
10
8
6
4
2
0
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEPT
OCT
NOV
DEC
Calender time

Figure 2.3 Representative profile description of the Arrow series soil

Representative Profile of the Arrow Series Soil.

HORIZON	DEPTH (cm)	DESCRIPTION
	0	
		Very dark greyish brown (10 YR 3/2)
		sandy loam friable slightly stony
		moderate medium subangular
		abundant fine fibrous roots
		sharp even boundary
	25	Brown (10 YR 5/3)
		sandy loam friable slightly stony
		moderate medium angular
		many distinct fine ochreous mottles
		rare fine fibrous roots
		narrow even boundary
	43	Dark greyish brown (10 YR 4/2) and
		light grey (2·5 Y 7/2)
		sandy loam loose slightly stony
		weak medium angular
		many distinct medium ochreous mottles
		rare fine fibrous roots
		sharp even boundary
IICg	100	Reddish brown boulder clay



(Source: Thomasson, 1971)

Table 2.1 Varieties used for field trials in 1983 and 1984
(Source NIAB Recommended Variety lists 1982/83)

Field Beans	-	Maris Bead (PBI)
	-	Small seed and round
	-	Early ripening
	-	Good standing power
	-	1000 seed weight - 417 g
	-	Crude protein - 26%
Spring Barley	-	Carnival (PBI)
	-	Very high yield
	-	Good malting quality
	-	Short, very stiff straw
	-	Good resistance to yellow and brown rust
	-	1000 seed weight - 45 g
Sugar Beet	-	Monoire (Miln Marsters)
	-	Above average sugar yield
	-	Relatively high impurities
	-	Low bolting
	-	Good resistance to downy mildew
* Grass	-	Frances (Van der Have, Netherlands)
	-	Perennial ryegrass
	-	Early variety
	-	High yield, particularly second half of year
	-	Heading date 46 (days after 1st April)
	-	Good persistance
	-	Good resistance to crown rust

* Only used in 1983

compaction treatment while regrowth was prevented by drought following a sward cut. Figures 2.4 and 2.5 present the field trial plan for 1983 and 1984 respectively.

There is no standard level of soil compaction on account of the extreme variability of field traffic, soil structure and weather (Soane, Dickson and Campbell, 1982). Therefore an arbitrary value of one complete wheeling of the plot was chosen to represent a variety of natural or induced topsoil compaction problems. The treatment was applied, post-sowing, by progressively wheeling across the entire plot with one pass of a John Deere 2140 tractor (wheelbase weight - 3500 kg; tyre inflation pressure - 0.84 kg cm^{-2}) at a speed of approximately 4 km hr^{-1}. The soil moisture content was measured gravimetrically, one hour before the compaction treatment was applied.

In 1983 a further treatment, 3,5,diiodo-4-hydroxybenzoic acid (DIHB), was also investigated. Wilkins, Wilkins and Wain (1977) found that DIHB had the capability of reducing the root growth inhibition induced by compacted soil and of increasing shoot length and seedling dry weight. It was envisaged that this compound might be extremely valuable in the field, in offsetting temporarily some of the detrimental effects of compaction and thereby maintaining crop yield. The chemical was applied to compact soil, with a knapsack sprayer, just after crop emergence, at a rate of 0.05 kg ha^{-1} active ingredient in 500 l ha^{-1} of water. This treatment was not repeated in 1984.

Many researchers have demonstrated that soil compaction reduces crop yield (Richards, 1953; Flocker, Trimm and Vomocil, 1960; Phillips and Kirkham, 1962; Draycott, Hull, Messem and Webb, 1970; Batey and Davis, 1971; Gooderham, 1977; Jaggard, 1977). However, they have failed to

Figure 2.4 Diagram of the 1983 soil compaction field trial site

SOIL COMPACTION TRIAL 1983.

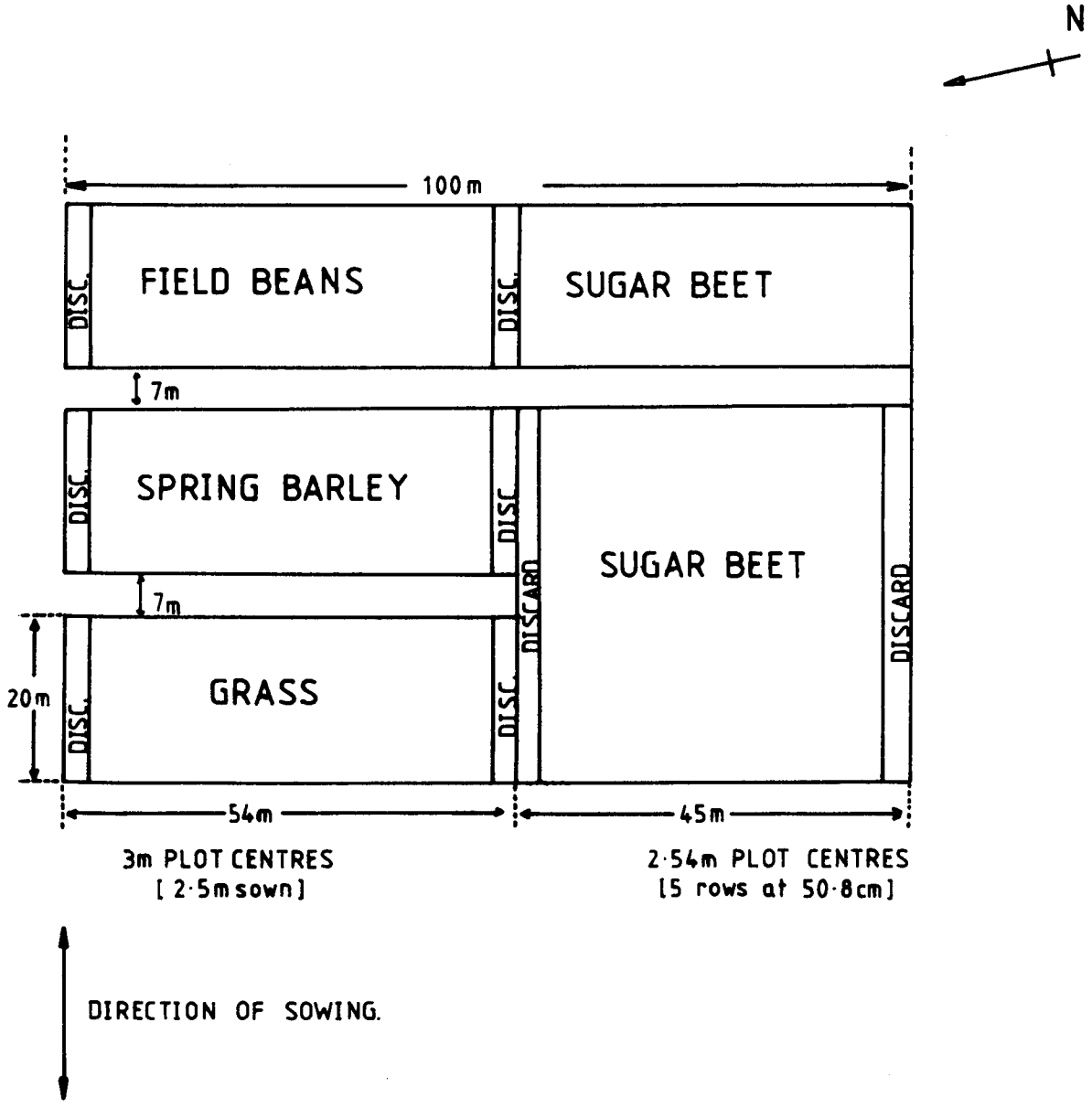
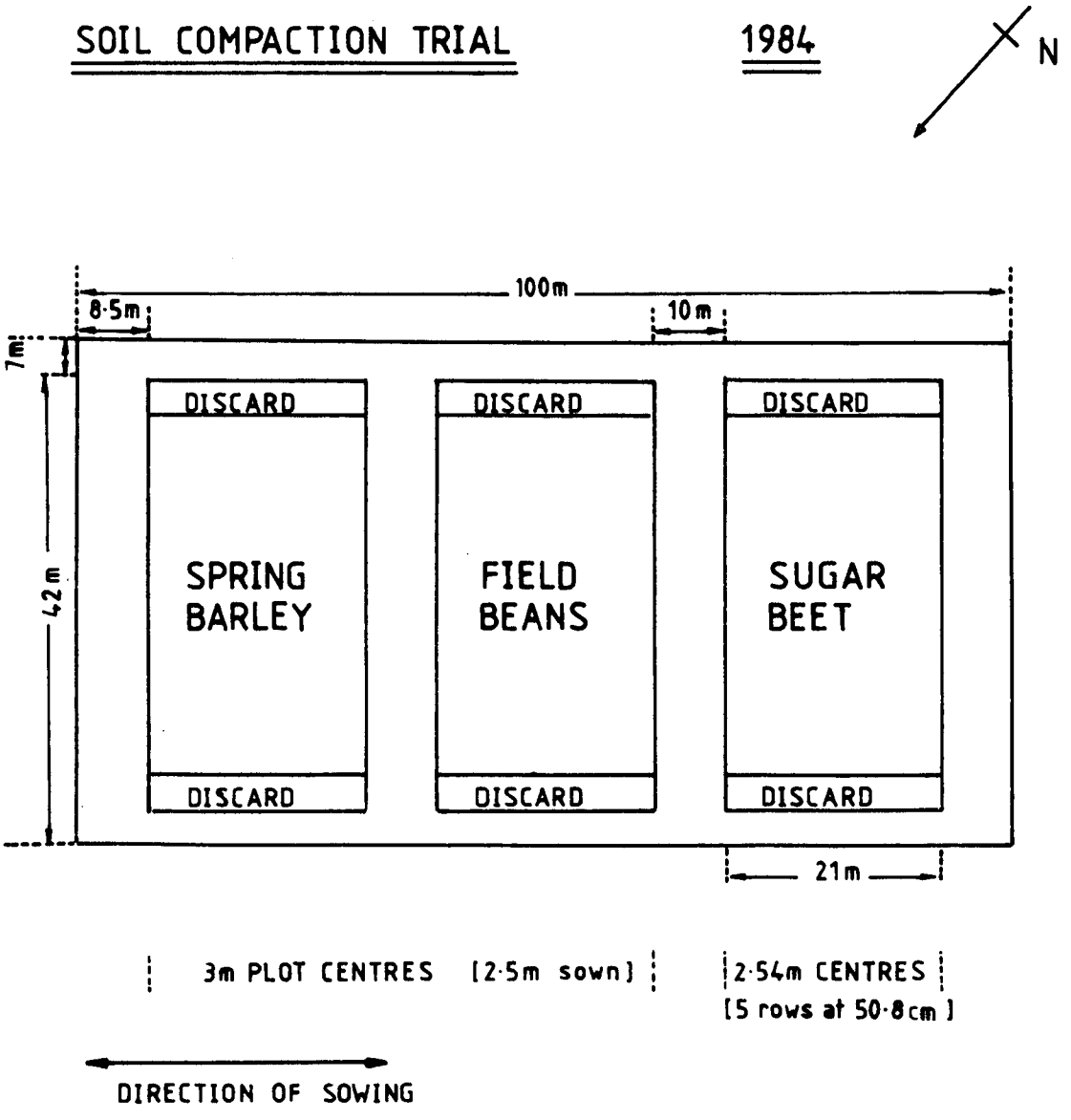


Figure 2.5 Diagram of the 1984 soil compaction field trial site

SOIL COMPACTION TRIAL 1984



distinguish between a reduced plant population and an impaired performance of individual plants as the major determinant of lost yield. In order to test the ability of the compact crop to compensate for low plant populations, replicated control plots were sown in 1983. It was the intention that they would be thinned to the population density and distribution of the compact treatment (Hebblethwaite and McGowan, 1980; Dawkins, 1982). However the crops, which were sown on 11th March, emerged through moist soil and the plant number was not reduced. A control thinned treatment was not included in the 1984 trial.

Details of the experimental plots, cultivations and management of the 1983 and 1984 field trials are presented in Tables 2.2 to 2.5.

In 1983 the nitrogen fertilizer (ammonium nitrate, Nitram, 34.5% N) had to be applied by hand to the spring barley because the wide, Nordsten-drilled, plots did not permit tractor application to be made without travelling on the crop. Each plot was divided into twenty equal units and 5% of the total nitrogen to be applied was broadcast, with a sand 'filler', onto each plot unit. However, the uniformity of application was poor and in 1984 the total nitrogen (Nitram, 34.5% N) was spread by tractor before the final cultivation and drilling. This proved to be a satisfactory method for the management of spring crops sown in wide plots.

Table 2.2 Experimental plot details 1983

	Field Bean	Spring Barley	Sugar Beet	Grass
Sowing Date	11 March	11 March	10 May	11 March
Seed Rate	220 kg ha^{-1}	180 kg ha^{-1}	75,000 seeds ha^{-1}	12 kg ha^{-1}
Method of Sowing	Nordsten drill	Nordsten drill	Stanhay Mark II precision drill	Nordsten drill
Experimental Design	randomised block	randomised block	randomised block	randomised block
Number of Replicates	4	4	4	4
Plot Size (m)	2.5 x 18	2.5 x 18	2.5 x 18	2.5 x 18
Inter-plant Distance (cm)	-	-	15	-
Inter-row Distance (cm)	11.9	11.9	50.8	11.9
Rows per Plot	21	21	5	21
Area of Final Harvest (m^2)	15	15	15	15
Date of Final Harvest	16 August	5 August	3 October	19 June

Table 2.3 Cultivations and management details of the 1983 field trial

	Field Bean	Spring Barley	Sugar Beet	Grass
Previous Crop	Potato	Potato	Potato	Potato
Post-harvest Cultivation (Autumn)	Chisel plough, twice	Chisel plough, twice	Chisel plough, twice	Chisel plough, twice
Seedbed Preparation (Spring)	Spring tine	Spring tine	Spring tine	Spring tine
Basal Seedbed Fertilizer (Ammonium nitrate)	None	None	None	None
Seedbed Cultivation	Rolled	Rolled	None	Rolled
Post-sowing Fertilizer kg ha^{-1} (Ammonium nitrate)	None	130 (90 + 40)	135	200 (100 + 100)
Pre-emergent Herbicide	Trietazine + Simazine (Remtal SC) 2.4 l ha^{-1}	None	None	None
Post-emergent Herbicide	None	Ioxynil, Bromoxynil (Stellox) 1.0 l ha^{-1} + MCPA (Mecoprop) 2.8 l ha^{-1}	Phenmedipham (Betanal E) 7.0 l ha^{-1} + Chloridazon (Trojan) 3.0 l ha^{-1}	2-3-6 TBA, MCPA, Dicamba and Mecoprop (Cambilene) 5.0 l ha^{-1}
Fungicide	Benomyl (Benlate) 1.0 kg ha^{-1}	Carbendazim + Tridemorph + Maneb (Cosmic) 4.0 kg ha^{-1}	None	None
Insecticide	Pirimicarb (Aphox) 0.28 kg ha^{-1}	None	None	None

Table 2.4 Experimental plot details 1984

	Field Bean	Spring Barley	Sugar Beet
Sowing Date	20 March	20 March	6 April
Seed Rate	220 kg ha^{-1}	180 kg ha^{-1}	75,000 seeds ha^{-1}
Method of Sowing	Nordsten drill	Nordsten drill	Stanhay Mark II precision drill
Experimental Design	randomised block	randomised block	randomised block
Number of Replicates	4	4	4
Plot Size (m)	2.5 x 21	2.5 x 21	2.5 x 21
Inter-plant Distance (cm)	-	-	15
Inter-row Distance (cm)	11.9	11.9	50.8
Rows per Plot	21	21	5
Area of Final Harvest (m^2)	22.5	22.5	20.0
Date of Final Harvest	6 September	13 August	17 September

Table 2.5 Cultivations and management details of the 1984 field trial

	Field Bean	Spring Barley	Sugar Beet
Previous Crop	Potato	Potato	Potato
Post-harvest Cultivation (Autumn)	Chisel plough, twice	Chisel plough, twice	Chisel plough, twice
Seedbed Preparation (Spring)	Fixed tine	Fixed tine	Fixed tine twice
Seedbed Fertilizer kg ha^{-1} (Ammonium nitrate)	None	150	135
Seedbed Cultivation	None	None	None
Post-sowing Fertilizer kg ha^{-1} (Ammonium nitrate)	None	None	None
Pre-emergent Herbicide	Trietazine + Simazine (Remtal SC) 2.4 kg ha^{-1}	Methabenzthiazuron (Tribunil) 2.25 kg ha^{-1}	Chloridazon (Trojan) 3.0 l ha^{-1}
Post-emergent Herbicide	None	None	None
Fungicide	None	Triadimefon (Bayleton) 0.5 kg ha^{-1} Carbendazim + Tridemorph + Maneb (Cosmic) 4.0 kg ha^{-1}	None
Insecticide	Triazophos (Hostathion) 0.85 l ha^{-1}. Pirimicarb (Aphox) 0.28 kg ha^{-1}	None	None

Chapter 3

SOIL PHYSICAL CONDITIONS

3.1 Introduction

Ideally, crops require a well structured, fertile soil to supply the water and nutrients required for growth and development. Crops are frequently grown in conditions which are far from ideal. Soils of poor inherent structure may form a barrier to plant emergence and they can restrict root growth. The extensive employment of field machinery may also impose structural problems on the soil. After the passage of a wheel a new set of properties assumes an importance in indicating the intensity and distribution of the compaction produced and the possible significance of these changes to crop growth (Soane, Blackwell, Dickson and Painter, 1981).

This chapter examines the principal soil properties which regulate crop growth and considers the manner in which they are changed by compaction. The effects of these properties upon root growth is also discussed.

3.2 Materials and Methods

The weather is known to exert a profound effect on the soil physical conditions (Soane, 1981) and so it was important that the data for all the series of field tests was collected as rapidly as possible.

3.2.1 Particle Size Distribution and Organic Matter

The particle size distribution is a basic physical determination and is used to assess the mechanical composition of the soil (Evans, 1979). It was measured by using the standard Bouyoucos hydrometer method (Bouyoucos, 1962). The organic matter content of the soil was determined by using the Walkley Black method as described by Bremner and Jenkinson (1960) and the pH was measured by using the procedure reported by Bascomb (1974).

3.2.2 Water Retention Characteristic

The gravimetric water content of the soil relative to an applied matric potential (Childs, 1942) was determined in 1984 from disturbed soil samples. Matric potentials to -0.2 MPa were produced with sand tension tables (Ministry of Agriculture, Fisheries and Food, 1979a) and a ceramic plate apparatus was used to develop potentials to a minimum of -1.5 MPa (Ministry of Agriculture, Fisheries and Food, 1979b). The soil samples were weighed daily and the moisture content was determined when the weight had remained constant for three consecutive days at a given potential.

3.2.3 The Proctor Compactability Test

The Proctor compactability test (Proctor, 1933) is based on the measurements of bulk density after the application of a defined stress and it is widely used by civil engineers as a standard (Soane et al., 1981).

Disturbed samples of known water content were impact loaded, with a 2.5 kg hammer, into a container of standard dimensions and this was weighed. The soil was then removed from the container and passed through

a 20 mm BS test sieve. Afterwards the sample moisture content was increased and the test was repeated. The full methodology for this test is specified by the British Standards Institution (1975).

Fine grained soils achieve a maximum compactability, measured as dry bulk density, at a water content which is dependent on the type and degree of the compactive stress.

3.2.4 Bulk Density

The dry bulk density was calculated in the top 10 cm of soil profile in 1983 and in 10 cm increments to a 30 cm depth in 1984 by the replacement method (Hughes, 1979). A Jarret auger was used to produce a 10 cm diameter, parallel sided hole, and this hole was lined with polythene and filled with a measured quantity of water. The technique is slow and errors may occur in determining whether the hole is completely filled. However, the location of the sample can be identified exactly and the results can be very accurate if the hole is carefully prepared and the risk of shattering is thereby minimised (Soane et al., 1981).

3.2.5 Vane Shear Strength

The vane shear strength (Marks, 1979) was measured with a hand vane tester (WF 30200, Wykeham Farrance Engineering Ltd. - 19 mm vane) at five locations on each plot. In 1983 the shear strength was measured only in the surface 2.5 cm but in 1984 it was measured at 2.5 cm increments to a depth of 12.5 cm, at one hour after applying the treatment.

In order to minimise errors a uniform rate of loading was applied to the torque head by rotating it at a standard speed while care was taken to ensure a 'clean' vertical penetration of the vane into the soil.

3.2.6 Cone Resistance

The cone resistance was measured with a Bush Digital Penetrometer (Anderson, Pidgeon, Spencer and Parks, 1980), fitted with a 12.9 mm diameter, 30° cone, to a depth of 21 cm at five separate locations in the plot. This machine is a solid state hand-held penetrometer measuring force with a strain-gauged transducer and depth with an accurate optical system. Readings were taken within three hours of completing the compaction treatment in 1983 and 1984. The soil was inherently stony and therefore discretion had to be used in interpreting the data.

3.3 Results and Discussion

3.3.1 Particle Size Distribution

The particle size distribution for the topsoil and subsoil samples from the experimental site is shown in Table 3.1. In 1984 the soil from the individual cropping areas was analysed separately with the object of investigating any inherent differences in the particle size distribution across the trial area. However the fractions of sand, silt and clay were found to be similar on all sample sites (Table 3.2).

Table 3.1 The particle size distribution of soil from the 1983 trial site

	% oven dry soil Organic matter°	% Coarse* sand (2mm-200µm)	% Fine sand (200-50µm)	% Silt (50-2µm)	% Clay (<2µm)
Top soil	1.4	52.4	25.6	13.3	8.7
Subsoil	0.91	54.7	25.2	12.1	8.0

* % insoluble residue

° % oven dry soil

Table 3.2 The particle size distribution of soil from the 1984 trial site

Depth (cm)	% Organic° carbon	% Coarse sand* (2mm-200µm)	% Fine sand (200-50µm)	% Silt (50-2µm)	% Clay (<2µm)	pH
Spring Barley						
0-30	2.15	58.5 ± 6.5	9.7 ± 1.7	16.0 ± 3.2	15.8 ± 1.5	6.5
30-60	0.60	64.8 ± 0.1	8.2 ± 0.1	13.4 ± 0.6	13.6 ± 0.6	6.7
60-90	0.52	69.5 ± 2.0	8.7 ± 1.5	9.3 ± 1.2	12.4 ± 0.6	6.5
90 +	0.20	76.8 ± 2.5	7.5 ± 2.4	7.8 ± 0.7	7.85 ± 0.6	6.7
Field Beans						
0-30	1.75	61.2 ± 0.2	10.3 ± 0.1	15.0 ± 0.6	13.5 ± 0.7	6.6
30-60	0.45	65.5 ± 0.3	10.2 ± 0.3	13.1 ± 1.2	11.3 ± 0.6	6.9
60-90	0.22	68.5 ± 1.5	10.1 ± 0.3	9.5 ± 1.3	11.9 ± 0.1	6.9
90 +	0.16	69.2 ± 2.4	6.5 ± 1.7	10.1 ± 1.9	14.2 ± 0.1	7.0
Sugar Beet						
0-30	1.91	57.1 ± 3.9	7.9 ± 3.1	18.1 ± 1.4	16.8 ± 0.3	7.0
30-60	0.75	59.2 ± 0.2	8.9 ± 0.2	17.9 ± 0.6	14.1 ± 0.5	7.0
60-90	0.47	60.3 ± 2.7	8.2 ± 2.2	18.7 ± 0.4	12.7 ± 0.2	7.0
90 +	0.18	53.4 ± 0.4	8.3 ± 0.1	15.9 ± 0.6	22.4 ± 0.9	7.1

* % insoluble residue

° % oven dry soil

The particle size distribution has been found to influence the relationship between soil strength and soil compaction. Chancellor (1971) found that soils which had a uniform distribution over a wide range of particle sizes offered less resistance to volumetric compression, at a given density and moisture content, than soils which consisted of particles from within a narrow size range.

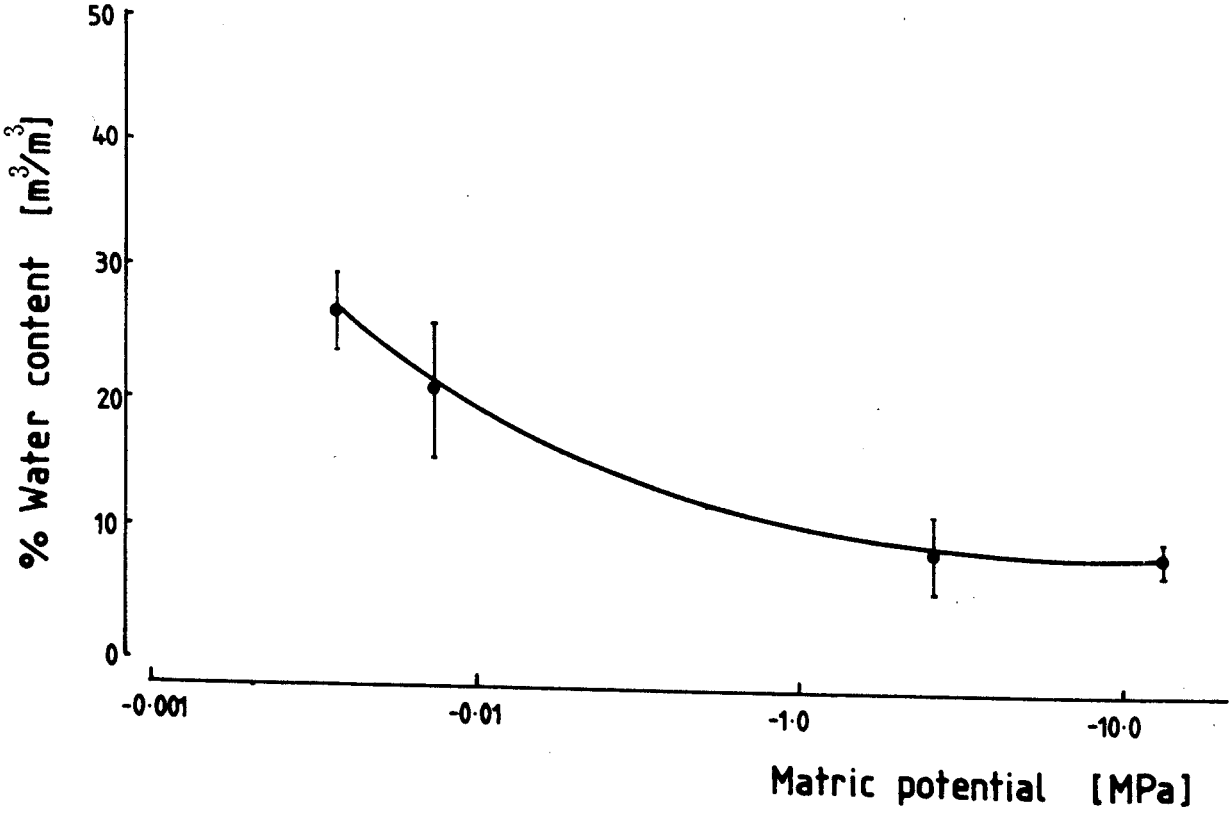
The percentage organic carbon content and pH of the soil is also shown in Table 3.2. The organic matter content varied slightly across the trial site and decreased with depth, as was expected. Davies (1975) reported the importance of the organic matter content of fine sandy soils in determining their structural stability, since organic matter has a cohesive action on soil aggregates. Russell (1973) stated that there was no critical organic matter content below which soil stability problems became significant, but from trials in Eastern England, he found however that an organic matter of less than 2.5% could result in serious difficulties in soil management. Soane (1975) studied fifty-eight Scottish soils and found a close negative correlation between the organic matter content and the maximum bulk density measured by the Proctor test.

The pH for crop growth was found to be within the acceptable limits at each sample site.

3.3.2 Water Retention Characteristics

The water retention curve for the topsoil (0-30 cm) from the 1984 trial site (Figure 3.1) indicates the characteristic water content at a specific matric potential. The water retention determinations are normally made on drying soil because of the hysteresis effect: A drying soil has a higher water content than a wetting soil (Archer, 1979).

Figure 3.1 Water retention curve of topsoil (0-30 cm) samples from the 1984 trial site


50
40
30
20
10
0
% Water content [m3/m3]
-0·001
-0·01
-1·0
-10·0
Matric potential [MPa]

At matric potentials below -100 kPa, a large difference in potential produced a relatively small change in the percentage soil water content. This result is important when studying the process of water extraction by roots and can account for discrepancies which may occur between the neutron probe, measuring water content and soil psychrometers, measuring water potential.

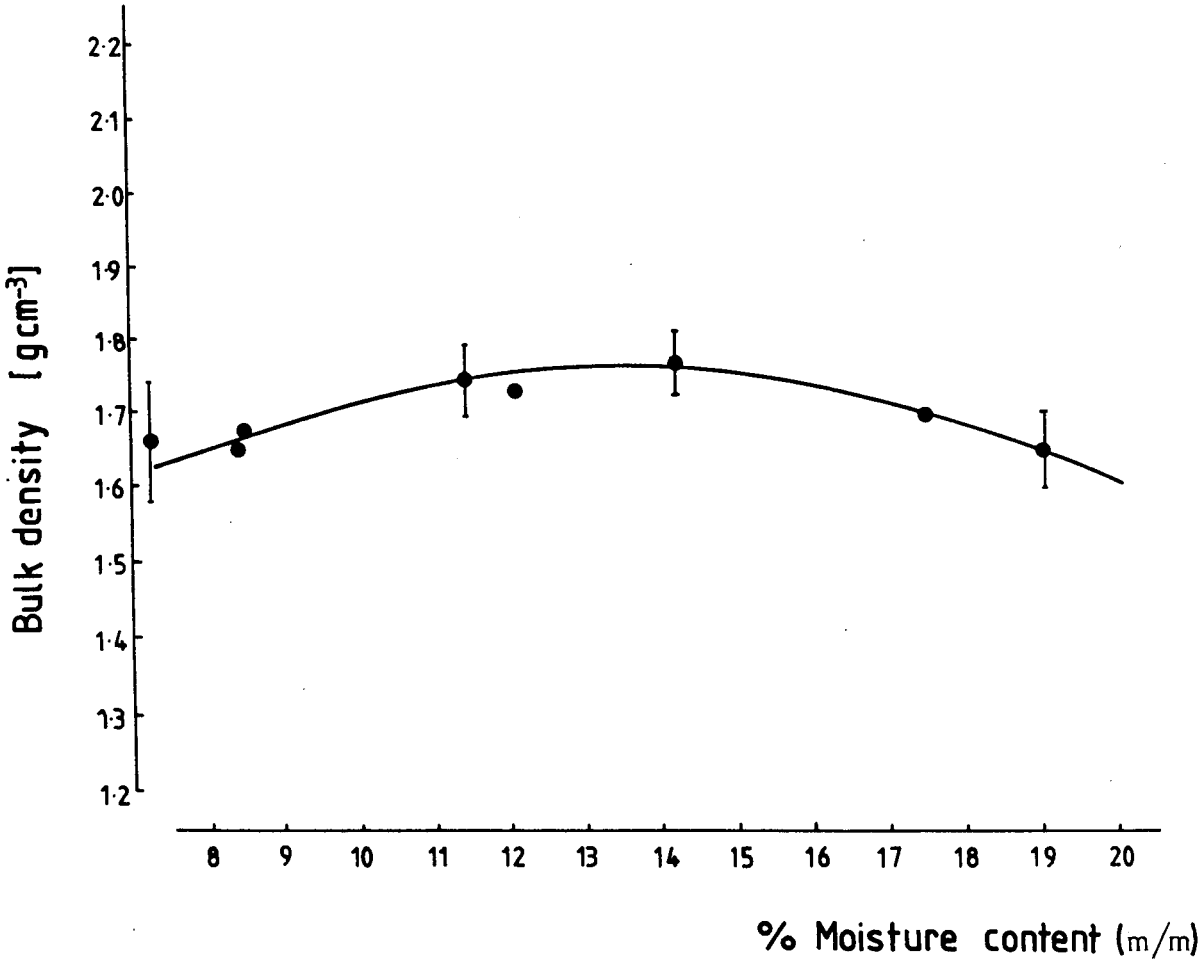
It was not possible to use the water retention data to identify treatment effects because measurements were made on disturbed, sieved soil samples as used in the Proctor compactability test (Sub-section 3.3.3). However, O'Sullivan and Ball (1982b) examined the moisture retention of undisturbed cores from direct drilled and ploughed, sandy loam soil. They found that at potentials lower than -3.0 kPa, the direct drilled, hence more compact, soil had a greater moisture content than the other. The reason is that there are more smaller, moisture retentive pores at high bulk densities compared with the large, readily drainable pores which predominate at low bulk densities (Mirreh and Ketcheson, 1972).

3.3.3 Proctor Compactability Test

The Proctor Compactability Test is used by agriculturalists to evaluate the state of compaction of field soils (Pidgeon and Soane, 1977) and it may also be used to show the dependence of compaction on moisture content (Soane et al., 1981).

The relationship between maximum bulk density and water content, as determined by the Proctor compactability test, is given in Figure 3.2 for disturbed topsoil samples from the 1984 trial site. The maximum bulk density was achieved at a moisture content of 14.3% (v/v). This 'optimum water content' effect is related to the lubricating action of water films at

Figure 3.2 Relationship between the dry bulk density and the moisture content of topsoil (0-30 cm) samples from the 1984 trial site, as determined by the Proctor compactability test


Bulk density [gcm⁻³]
2·2
2·1
2·0
1·9
1·8
1·7
1·6
1·5
1·4
1·3
1·2
8
9
10
11
12
13
14
15
16
17
18
19
20
% Moisture content (m/m)

water contents below the optimum and to the limited air available for displacement, above the optimum (Soane et al., 1981).

Campbell, Stafford and Blackwell (1980) found that the optimum water content displayed a close similarity to the plastic limit and also to the water content at field capacity. In both years the water content at the time of applying the compaction treatment (Sub-section 3.3.6) was very close to the optimum water content.

The compactability of a soil is dependent on the following soil properties: Water content, organic matter, particle size distribution, plasticity index and clay mineralogy (Soane et al., 1981). However the Proctor compactability of a soil is also a function of the size, shape and confinement of the sample and of the type, duration and amount of compactive stress (Soane et al., 1981). Therefore, when used for studies on soil compaction by agricultural vehicles, the Proctor test has several limitations because it makes use of soils in a remoulded condition while the stresses applied are very different from those produced by wheels.

However Soane et al. (1981) reported a close correlation between the empirical laboratory test and the behaviour of soils in the field. The Proctor test can also provide a useful guide to the severity of compaction caused by undertaking field operations at a particular moisture content, in respect of a specific soil.

3.3.4 Bulk Density

The dry bulk density of a soil is defined as the mass per unit volume of dry soil in its undisturbed state and as such it is inversely correlated with total porosity (Hughes, 1979). Soil compaction increased the soil dry bulk density (Table 3.3) in both years and in 1984 to a depth of 30 cm.

Table 3.3 Dry bulk density of the soil as influenced by soil compaction in 1983 and 1984

Depth (cm)	Dry bulk density ($g\ cm^{-3}$) Control	Compact	SED	Sig*(3DF)	% soil moisture content (v/v)
1983					
0-10	1.07	1.48	0.041	$p<0.01$	14.1
1984				Sig*(6DF)	
0-10	1.03	1.51	0.057	$p<0.05$	13.6
10-20	1.61	1.77	0.057	NS	14.4
20-30	1.70	1.94	0.057	NS	12.5

* level of statistical significance

The effects of soil compaction on bulk density has been studied by many researchers (Eavis, 1972; Pidgeon, 1980; Blackwell and Soane, 1981). However, there is confusion with regard to the maximum depth to which the effects of compaction can be found. Blake, Ogden, Adams and Boelter (1960) detected an increase in bulk density, due to packing, down to a depth of 40 cm but Gooderham (1976) reported that topsoil compaction increased the bulk density only in the top 8 cm of the soil profile. Voorhees, Senst and Nelson (1978) found that the maximum depth to which the density had been increased by topsoil compaction was 15 cm.

Changes in bulk density as such have a limited use as an absolute indication of compaction and may be poorly correlated with plant growth responses (Trouse, 1966). However the indirect effects of bulk density on plant growth cannot be disregarded. Kemper, Stewart and Porter (1971) found that an increase in bulk density from 1.10 g cm^{-3} to 1.60 g cm^{-3}, at a constant matric potential of -0.03 MPa, resulted in a reduced hydraulic conductivity and a consequential reduction in the flux of water uptake.

3.3.5 Vane Shear Strength

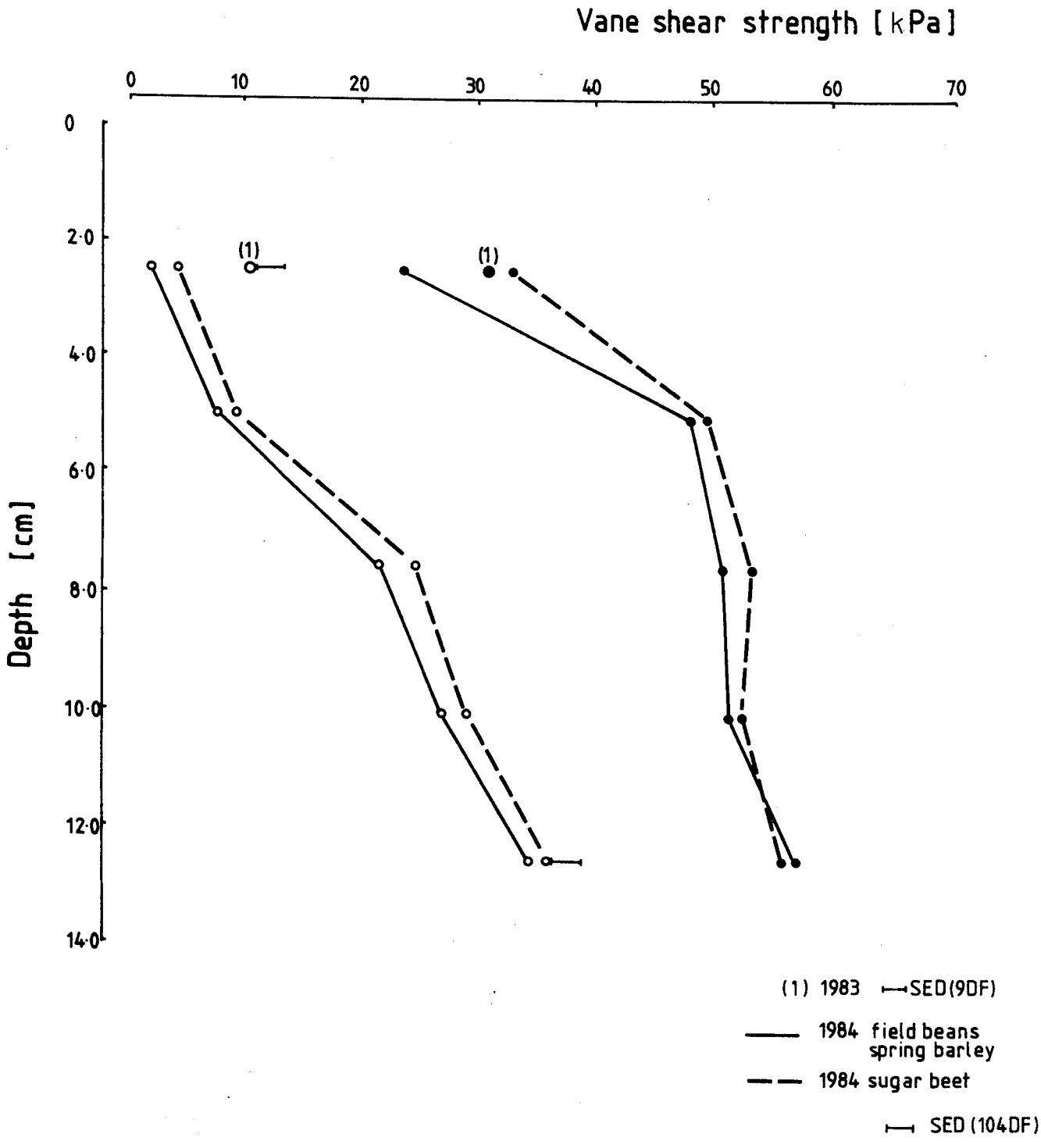
Shear strength is defined as the force required to cause sliding between two soil surfaces of unit area (Payne and Fountaine, 1952). It is considered to be a function of the cohesion between soil particles and the intergranular friction and it varies with the soil structure, moisture content and bulk density (Marks, 1979).

There was a significant difference ($p<0.001$) between the shear strength of the control and the compact treatments at the seedbed depth (1983) and down the profile in 1984 (Figure 3.3). The strength of both treatments increased with depth but the compact soil reached a 'highly consolidated' value, as defined by Marks (1979), at a depth of 6 cm. The greatest treatment difference occurred between a depth of 2.5 cm and 5.0 cm but the maximum shear strength of 57.3 kPa was found at a depth of 12.5 cm in the compact profile.

Soil strengths of 66 kPa for a heavily wheeled sandy loam soil were reported by Ball and O'Sullivan (1982), who found that a seedbed shear strength of 65 kPa was sufficient to reduce significantly the population of spring barley. However, root extension can be inhibited at soil strengths as low as 30 kPa (Barley, Farrell and Greacen, 1965).

Compact soil offers a greater strength to emerging seedlings and can become more pronounced throughout a dry season. Ball and O'Sullivan (1982) studied the natural strengthening of a soil by drying in the spring and early summer. They found that a compact seedbed strengthened to a greater degree than a ploughed seedbed for a similar change in water content.

Figure 3.3 Vane shear strength as influenced by soil compaction in 1983 and 1984. Control (o); Compact (●)


Vane shear strength [kPa]
0
10
20
30
40
50
60
70
Depth [cm]
0
2·0
4·0
6·0
8·0
10·0
12·0
14·0
(1)
(1)
(1) 1983 SED(9DF)
1984 field beans
spring barley
1984 sugar beet
SED (104DF)

3.3.6 Cone Resistance

The penetrometer is the most widely used instrument for assessing soil strength in situ but the empirical nature of the data produced is a major disadvantage. The penetrometer gives a better spatial resolution than the vane shear tester and is capable of detecting high strength layers which may limit root growth. However, vane shear strength is related to crop emergence more closely than is cone resistance and it has been found to give a good single index of seedbed strength (O'Sullivan and Ball, 1982a).

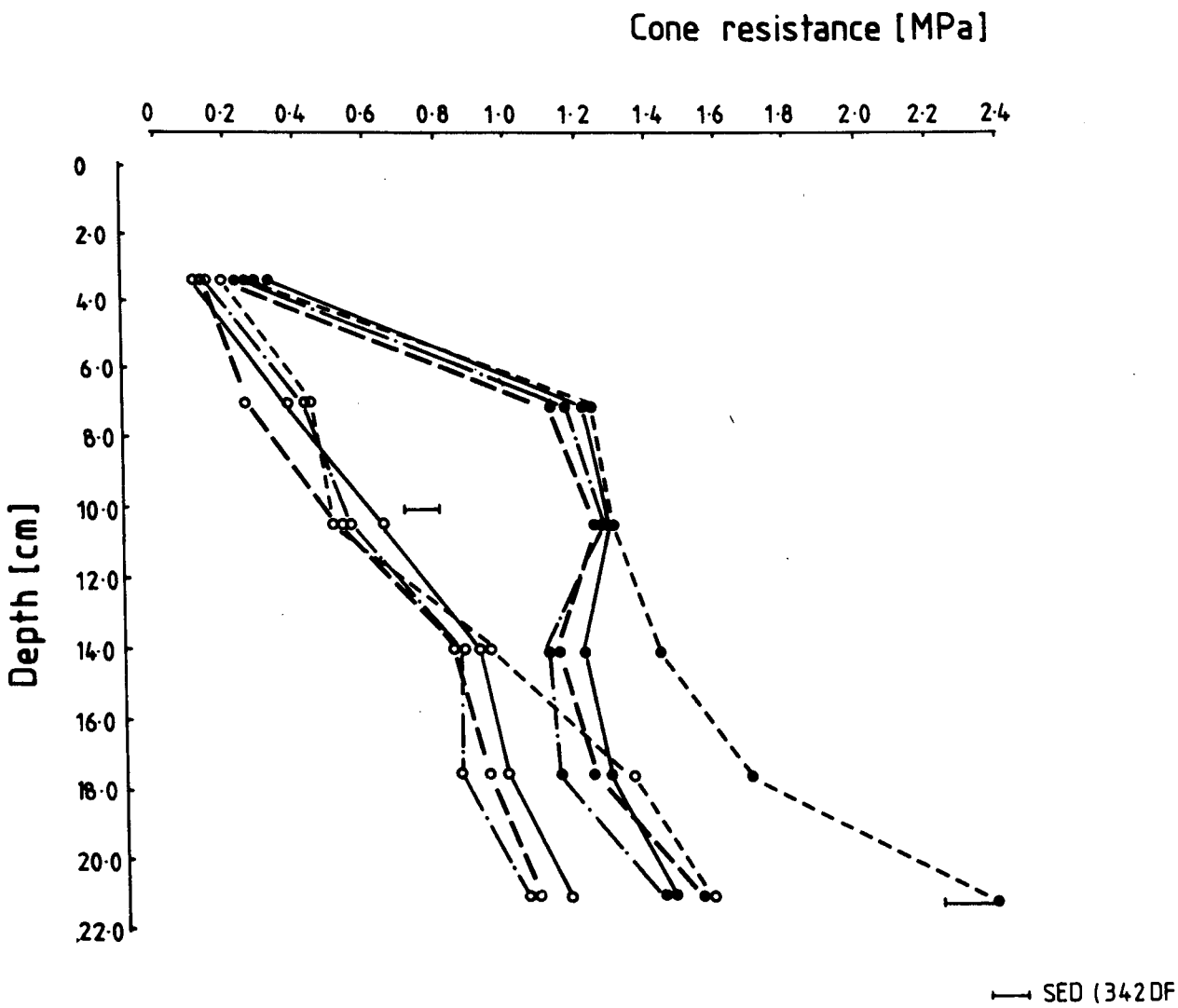
In order to investigate any changes in inherent soil structure across the trial site, the penetrometer cone resistance was measured for each treatment and each crop in 1983 (Figure 3.4). Soil compaction significantly increased ($p<0.001$) the cone resistance between a depth of 7.0 cm and 10.0 cm. This result agrees with Ball and O'Sullivan (1982) who reported a rapid increase in the cone resistance in relation to depth with a maximum between 7.0 cm and 10.0 cm. They speculated that this feature may be a characteristic of heavily compacted seedbeds since similar findings were reported by Campbell, Dickson and Hunter (1980).

The cone resistance of the sugar beet area, measured during dry weather, was greater than any other area of the trial site. This may have been due to a lower soil moisture content as has been reported by many researchers (Williams and Shaykewich, 1970; Eavis, 1972; Voorhees, 1983). The effect of soil moisture content on cone resistance was greater in compact soil.

It was therefore difficult to assess the extent to which the compaction treatment had contributed to an increase in soil strength. For

Figure 3.4 The penetrometer cone resistance of control (o) and compact (●) soil in 1983

Field beans (—·—)
Spring barley (— —)
Sugar beet (- - -)
Grass (——)


Cone resistance [MPa]
0
0·2
0·4
0·6
0·8
1·0
1·2
1·4
1·6
1·8
2·0
2·2
2·4
Depth [cm]
0
2·0
4·0
6·0
8·0
10·0
12·0
14·0
16·0
18·0
20·0
22·0
SED (342 DF)

this reason, Chancellor (1976) suggested that the cone resistance should be measured when the whole profile is at field capacity. However, this was not possible for sugar beet because the crop had to be sown after the risk of frost had subsided.

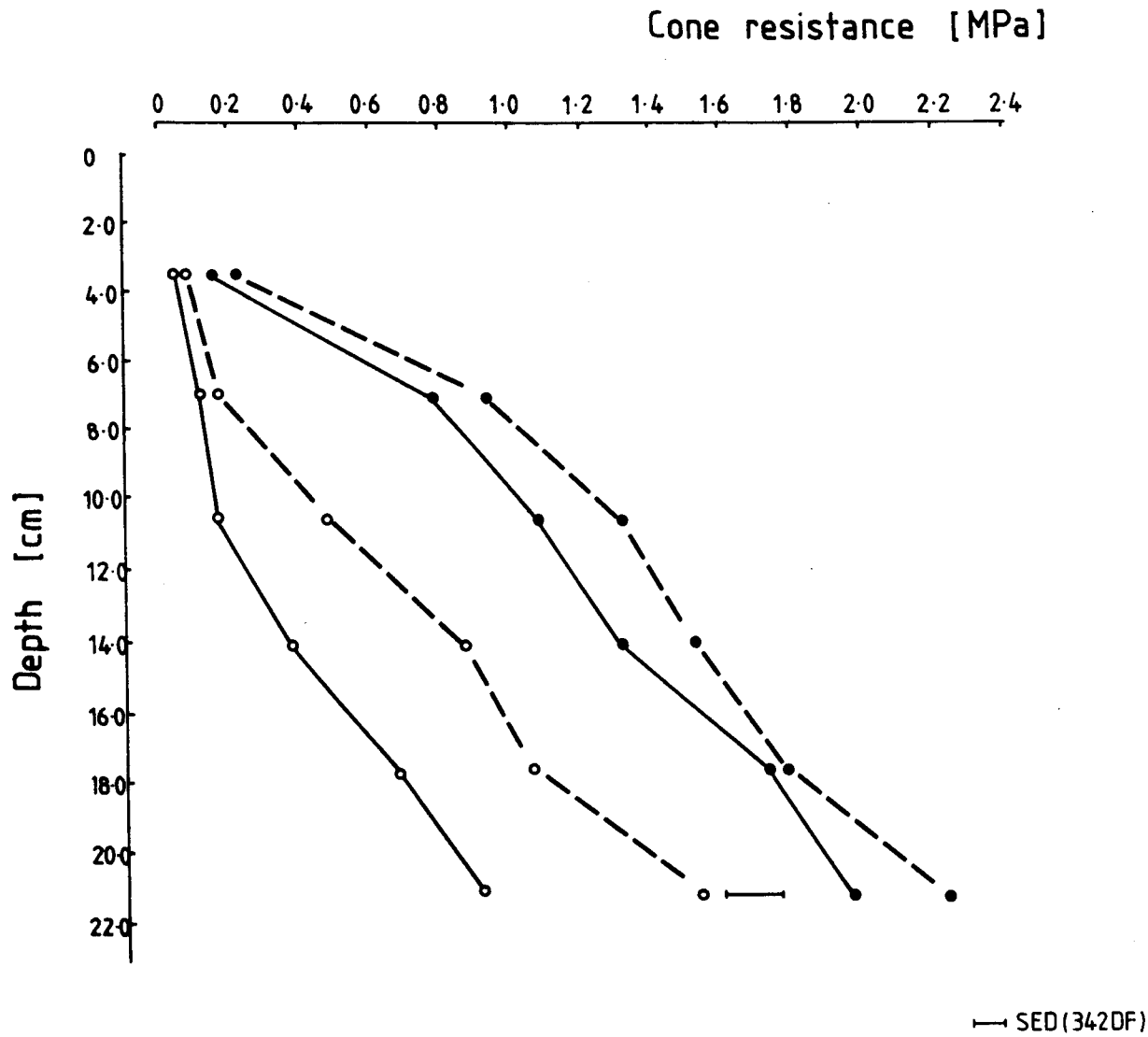
The topsoil moisture contents at the time of compacting the soil were 14.1% (v/v) and 13.9% (v/v) for crops sown on 11th March and 10th May, 1983, respectively. In 1984, values of 13.6% (v/v) and 13.5% (v/v) were obtained for crops sown on 20th March and 6th April, respectively.

In 1984 (Figure 3.5) compaction significantly increased ($p<0.001$) the cone resistance at all depths when measured at the same moisture content. The effect of the drier sugar beet seedbed on cone resistance was again evident.

Some useful correlations have been made between cone resistance and root growth (Taylor and Ratliff, 1969; Taylor, 1971; Gooderham, 1973; Houben, 1974; Bowen, 1976) but there are objections which arise from biological considerations. Plant roots are able to penetrate soils which offer much higher resistance to metal probes than the pressure at which root growth has been found to stop (Taylor and Burnett, 1964; Whiteley, Utomo and Dexter, 1981). Eavis and Payne (1969) found that a penetrometer probe required a pressure of between four and eight times greater than the roots in order to penetrate the same soil. This suggests that plant roots may differ from probes in the mechanism of soil penetration. Stolzy and Barley (1968) found that there was a more efficient distribution of the stress applied by the root tip, possibly because of a radial mode of expansion. It was also found that there was less friction between the root and the soil; a factor which may constitute as much as 42% of the penetrometer point resistance (Farrell and Greacen, 1966).

Figure 3.5 The penetrometer cone resistance of control (o) and compact (●) soil in 1984

Field beans and spring barley (——)
Sugar beet (- - -)


Cone resistance [MPa]
0
0·2
0·4
0·6
0·8
1·0
1·2
1·4
1·6
1·8
2·0
2·2
2·4
Depth [cm]
0
2·0
4·0
6·0
8·0
10·0
12·0
14·0
16·0
18·0
20·0
22·0
SED (342DF)

The cone resistance at which root elongation is reduced has been examined by many workers but the results are inconsistent. Greacen, Barley and Farrell (1969) reviewed all the available literature on the probe pressure at which root elongation ceased and they found a variation between 0.8 MPa and 4.0 MPa. Gooderham (1973) reported that the root elongation of peas, tomatoes and ryegrass was reduced by 50% at a cone resistance of 1.5 MPa, but Ehlers, Kopke, Hesse and Bohm (1983) found that the limiting penetrometer resistance for root growth was as large as 3.6 MPa. However there is some agreement that root extension is reduced at cone resistances above 2.0 MPa (Taylor and Burnett, 1964; Taylor, Roberson and Parker, 1966; Mirreh and Ketcheson, 1972; Hemsoth and Mazurak, 1974; Grimes, Miller and Wiley, 1975; Voorhees et al., 1978; Bar-Yosef and Lambert, 1981).

The cone resistances found in the sugar beet profile attained this limiting value in both years. Although it was not feasible to measure the soil strength of the other cropping sites as the soil dried, it is probable that the compact soil profiles offered high resistances to root growth later in the season.

This chapter has shown how soil compaction changes the physical properties of the soil. The way in which these changes affect the shoot and root growth, the water status of the plant and the soil and the crop yield will be seen in the following chapters.

Chapter 4

CROP GROWTH

4.1 Introduction

The reduction in the yield of a number of crops as a result of soil compaction has been fully documented (Phillips and Kirkham, 1962; Kubota and Williams, 1967; Batey and Davies, 1971; Fisher, Gooderham and Ingram, 1975). However, while many researchers have studied the effects of mechanical impedance on root growth and development (Mirreh and Ketcheson, 1972; Gooderham, 1973; Ehlers, Kopke, Hesse and Bohm, 1983) there is only limited information available on the way in which soil compaction affects the shoot growth and development of agricultural crops. This information is vital to achieve an understanding of how soil compaction reduces crop yield and it was therefore considered in detail in this work.

This chapter examines the effects of soil compaction on the growth, development and yield of field beans, spring barley and sugar beet crops under similar climatic conditions and soil type.

4.2 Materials and Methods

4.2.1 Crop Emergence

The rate of crop emergence was calculated in all crops by counting the number of plants in three adjacent $^1/_3$rd of a meter rows each day until the plant population was stable for three consecutive days.

4.2.2 Mineral Analysis

In 1984 the dried samples from two growth analyses were retained from the compact and control treatments and were analysed for nitrogen, potassium, phosphorus, magnesium, manganese, sodium and calcium. The mineral analyses were conducted according to the procedures detailed in Technical Bulletin No. 27 'The Analysis of Agricultural Materials' (Ministry of Agriculture, Fisheries and Food, 1973).

4.2.3 Analysis of Crop Growth by Sequential Harvesting

The same sampling procedure was used in both years but differed between crops. Three adjacent $^1/_3$rd of a meter rows of spring barley were harvested from each plot. This method proved to be more accurate, i.e. resulted in a lower coefficient of variation, than sampling one complete meter row of crop because the plants tended to compensate for low vigour across the row to a greater extent than within the row. The field beans emerged unevenly in both years and compaction reduced substantially the population of sugar beet and thus the sample size, taken from row length, was too small to account for the variation between plants. Therefore, twenty adjacent field bean plants were cut at the soil surface and all the plant tissue was collected. Ten sugar beet plants were harvested at each sampling date, using a garden fork to recover as much as possible of the tap root.

All plants were harvested from within a designated area, at least 0.5 m from the previous harvest site and the plot ends in order to minimise any edge effects (Austin and Blackwell, 1980). The frequency with which the spring barley and field beans were harvested was regulated by crop

growth: Samples were taken weekly during the log phase of growth (Causton and Venus, 1981) in 1984. The frequency of sampling the sugar beet was restricted by low plant populations in the compact treatments and therefore the time of each harvest was determined by visual inspections of crop growth.

For each harvest, plants were removed from the field in large polythene bags and transferred to a cold room (1°C temperature) for storage until they could be analysed.

4.2.3.1 Dry matter

The samples were removed from the cold room and any fibrous root matter was removed. The areas of the leaf laminae were then measured using a moving belt electronic planimeter. The samples were further sub-divided as follows: spring barley into stems, ears and then grains; field beans into stems, buds, flowers and pods, and sugar beet into petioles, crowns and roots. The reproductive components were counted and the stem length was measured before the plant material was dried in an aerated oven at 80°C (+/- 5°C) for 48 hours. It was then weighed on a top pan balance and retained for mineral analysis. As the plants developed, the initial plot samples were further sub-divided into representative ten plant sub-samples before analysis.

4.2.4 Monitoring of Field Bean Flower and Pod Development

The development of flowers and pods on the field bean treatments was monitored on all replicates by labelling ten plants per plot and by counting the number of flowers and pods on each plant, weekly, from the beginning of flowering until harvest.

4.2.5 Final Harvest

The yields of spring barley and field beans were assessed from an undisturbed area of crop in the centre of each plot and this was harvested at maturity with a 'Walter and Wintersteiger' plot combine harvester. A strip of crop on either side of the cutter bar width was not included in the harvest weight, in order to avoid edge effects. A sub-sample was removed from the combine sample to determine the seed moisture content while the mean grain weight of 250 g of oven dried sample was recorded using a 'Decca Mastercount' electronic seed counter.

A growth analysis was taken at final harvest to determine the components of yield. Sub-sample yields were determined from hand threshed samples and these were used in preference to combine yields because of their close correlation to the plant components which were measured from the same sample.

The sugar beet crop was 'lifted' and 'topped' by hand and the root and shoot fresh weight was recorded in the field. The percentage sugar content was determined in the laboratory using the standard polarimetric technique described by Houlden (1979).

4.2.6 Monitoring of Tiller Development in Spring Barley

The production of tillers by the spring barley crop was monitored at 38, 45, 52 and 59 days after sowing and at final harvest, in 1984. On each date, coloured wire rings were placed over all tillers which had been produced since the last observation. A different coloured ring was used for each date. At final harvest, the ringed plants (10 per plot, 4 replicates per treatment) were taken to the laboratory and the number and colour of each

ring recovered on fertile and dead tillers were recorded. The dry grain weight from each tillering date was also recorded.

4.3 Results and Discussion

Soil compaction resulted in a large variation in the time of seedling emergence and in the plant distribution within the plots. Consequently, growth analysis of the non-uniform compact plots produced extremely variable data such that some large treatment differences were found to be not statistically significant. This should be considered when studying differences between the treatments in this thesis.

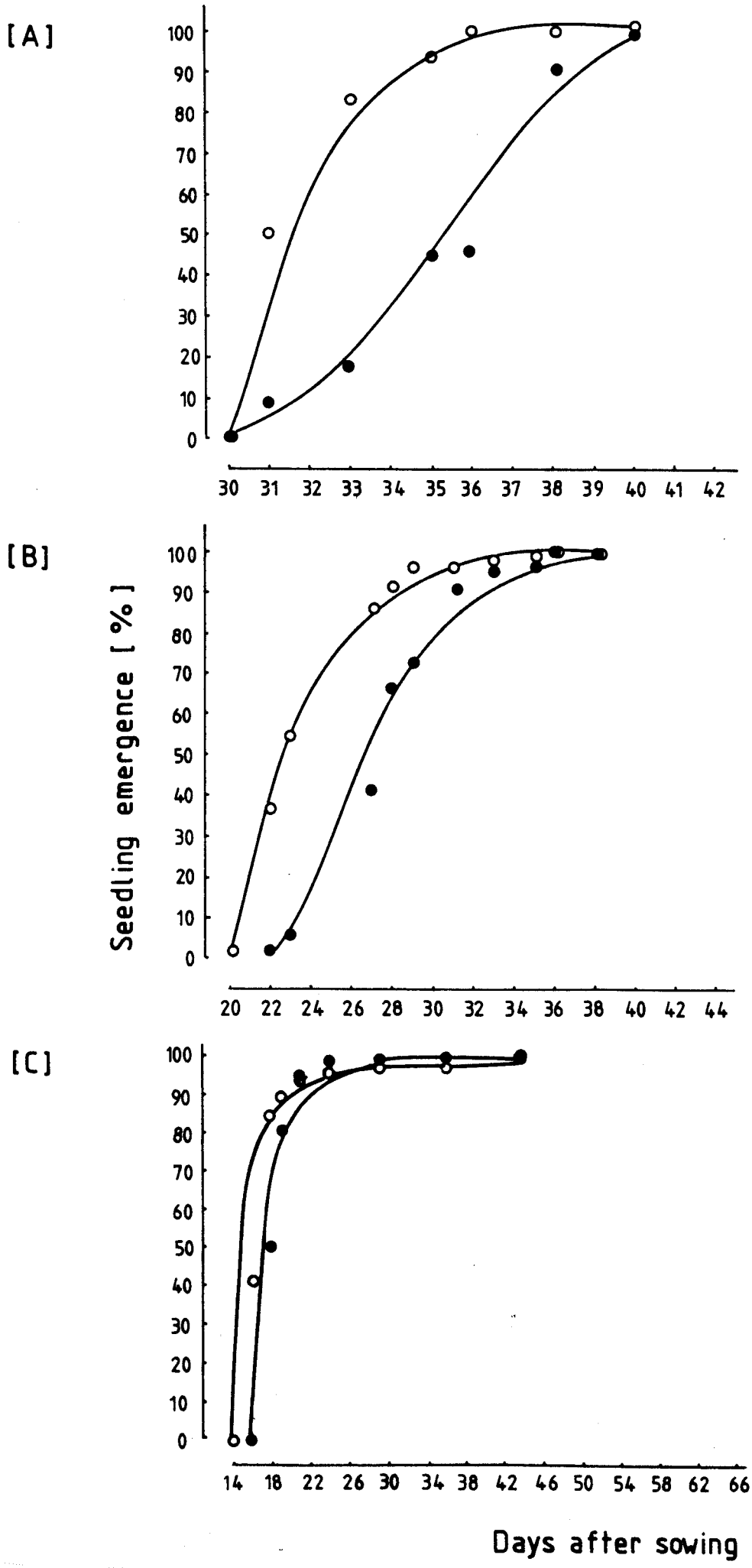
4.3.1 Plant Emergence and Population

The reduction in the population of plants grown in compacted soil is an important factor responsible for the loss of yield on these soils. Induced topsoil compaction can reduce seedling emergence by forming impenetrable barriers similar to those produced naturally by raindrop action and these are called soil 'caps'. The process of cap formation involves the dispersion of soil particles, the horizontal orientation of the long axis of the particle and the densification upon drying (Hillel, 1960).

In 1983, the plant populations of field beans (Table 4.4) and spring barley (Table 4.5) were not significantly changed by compaction but the population of sugar beet plants (Table 4.2), which emerged sixty days later than the other crops, and in drier soil, was significantly reduced ($p<0.001$) by 35% in compacted soil.

In 1984, soil compaction delayed the emergence of all crops (Figure 4.1) and reduced the final plant populations of field beans (Table

Figure 4.1 The effect of soil compaction of the emergence of field bean (A), spring barley (B), and sugar beet (C) in 1984, expressed as a percentage of the final plant number. Control (o); Compact (●).
[see Appendix 2 for statistical analysis]


[A]
[B]
[C]
Seedling emergence [%]
Days after sowing

4.4), spring barley (Table 4.5) and sugar beet (Table 4.2) by 41% (NS), 50% ($p<0.01$) and 64% ($p<0.001$) respectively.

Soil conditions which reduce the plant population can be particularly deleterious to the yield of sugar beet which is precision-drilled with monogerm seed. Plant populations of greater than 70,000 plants per hectare are necessary for optimum yield (Hull and Jaggard, 1971) but if the population falls below 51,000 plants per hectare (as in the 1984 trial), this may lead to a reduction in the root and sugar yield of about 10% (Holliday, 1960), because plant growth cannot compensate fully for the low plant numbers below this population.

A reduced plant population of various crop species in compacted soil has also been reported by many other researchers (Bakermans and De-Wit, 1970; Perry, 1973; Jaggard, 1977; Soane, Dickson and Campbell, 1982).

The effect of the compacted seedbed on plant population varied between 1983 and 1984 primarily as a result of the soil moisture content at emergence. In 1983 soils remained moist until after the beginning of May and thus the emergence of field bean and spring barley was unaffected by compaction. However, in 1984, the rainfall was low over the emergence period, resulting in high soil strength and consequently plant numbers were reduced in all crops.

The influence of soil moisture on the emergence of seedlings in compact seedbeds has been well documented. Carnes (1934) demonstrated that soil moisture was important in crust formation and he found that the slower the drying rate of the crust, the greater its strength because fast drying rates decreased cap strength by increasing surface cracking (Gerard, 1965).

Royle (1973) also found that the rate of drying and the moisture content of the soil in the capped layer were major determinants of the ability of a soil crust to act as a mechanical barrier.

In arid regions the formation of soil caps can be prevented by light applications of water (Prihar and Chowdhary, 1977).

The seedling has to expend extra energy to push through the hard crust and if the energy developed by the plant is not greater than the resistance of the crust to penetration, the seedling will die. It was previously believed that crusts reduced plant emergence by affecting the gaseous exchange and by limiting the oxygen supply to the germinating seeds. However Grable (1966), who reviewed the literature concerning seedling emergence through soil caps, found that crusts limited plant populations by preventing emergence rather than germination. He found that seeds germinated and remained alive for several days beneath the crust. If lack of oxygen had been a limitation, germination would not have occurred.

The ability of a seedling to emerge in a compacted seedbed has been found to be related to the seed size. A soil cap which was not strong enough to restrict the emergence of cereals severely affected the establishment of smaller seedbed crops such as sugar beet and vegetables (Davies, 1975).

This response was not necessarily related to a crop species because Townsend (1972) found that the emergence of large seeds of Cicer milkvetch was significantly greater than that of small seeds of the same species. Plates 4.1 and 4.2 show the emergence, in compacted soil, of field beans and spring barley respectively.

Plate 4.1 The emergence of a field bean seedling through compacted soil

Plate 4.2 The emergence of a spring barley seedling through compacted soil

4.3.2 Total Dry Matter Production

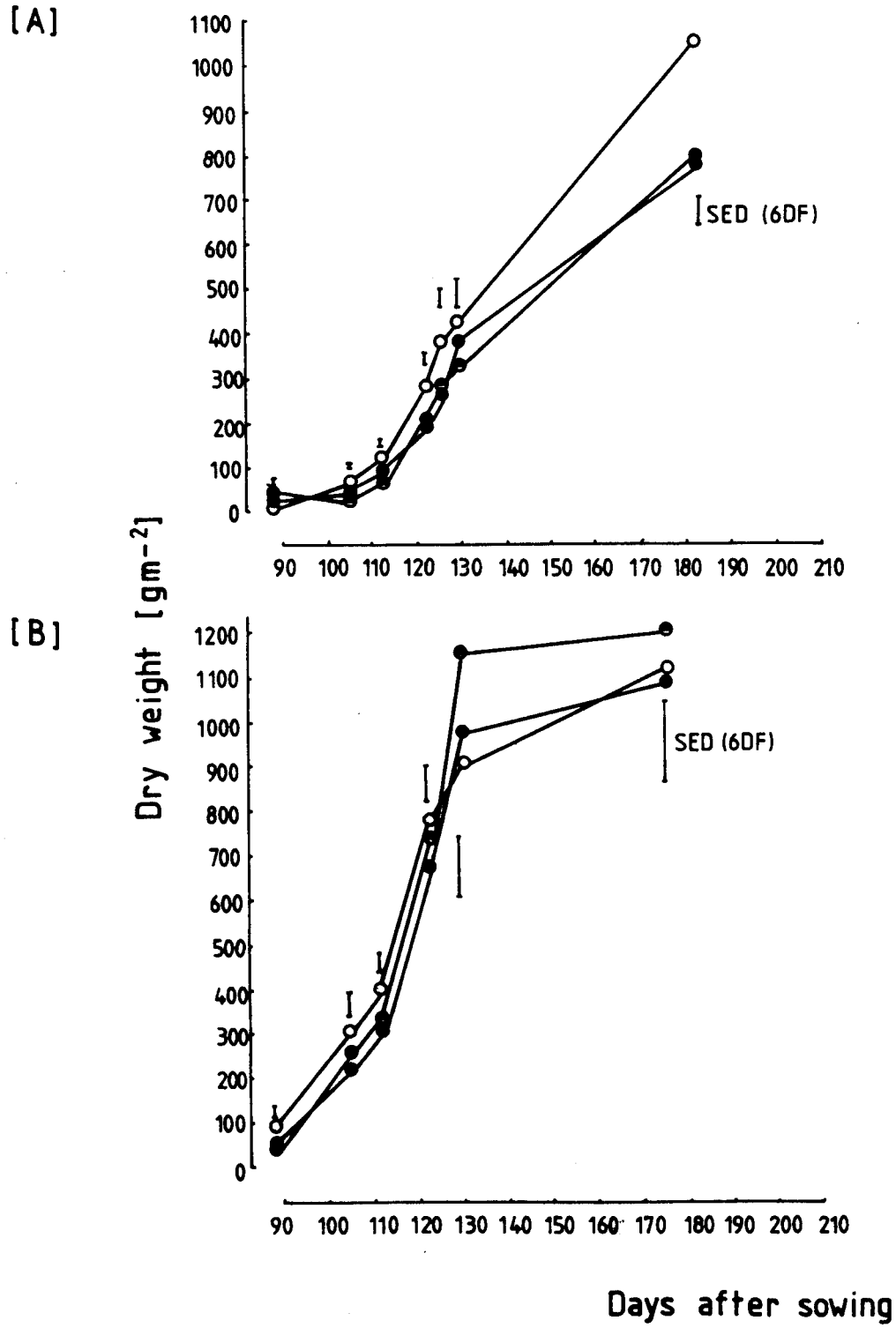
The total dry matter production per unit area of field beans and sugar beet was reduced by soil compaction throughout the 1983 season. However the dry matter production of spring barley was not reduced by the compaction treatment (Figure 4.2). Indeed at 128 days after sowing, the greater dry weight of the compact barley crop relative to the control may have been attributable to a delay in the senescence of the compact crop. This hypothesis was substantiated by visual inspection, which showed that leaves of the compact crop remained green for longer than those of the control. There was also found to be a greater water use by the compact treatment at the end of the monitoring period (Sub-section 7.3.6). The effect of soil compaction on plant senescence is discussed in Sub-section 4.3.12.

The DIHB soil treatment did not alleviate the reduction in total dry weight found in compacted field bean and sugar beet treatments. Although DIHB treated spring barley had the greatest total dry weight after mid-July (129 days after sowing) the difference between the treatments was not found to be significant.

The dry matter production, expressed on a per plant basis, was reduced by soil compaction in field beans and sugar beet, but not in spring barley (Figure 4.3).

The sugar beet plants did not fully exploit the increased amount of light and water made available by a large reduction in the plant population, as a result of the compaction treatment. This suggested that compaction had not only reduced crop emergence but it had also impaired the individual plant performance throughout the growing season. The lack

Figure 4.2 The total dry matter production per unit area of field bean (A), spring barley (B) and sugar beet (C) in 1983, as influenced by control (o), compact (●) and DIHB (⊖) treatments


[A]
[B]
Dry weight [gm-2]
SED (6DF)
SED (6DF)
90 100 110 120 130 140 150 160 170 180 190 200 210
Days after sowing

[C]

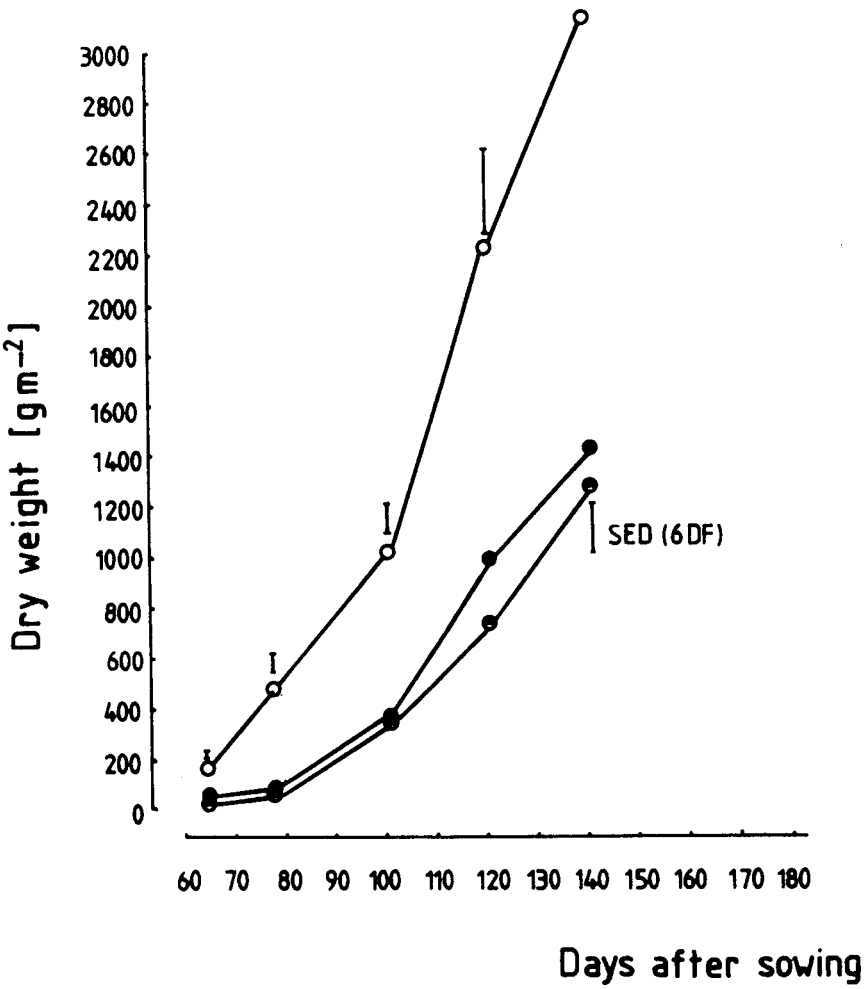
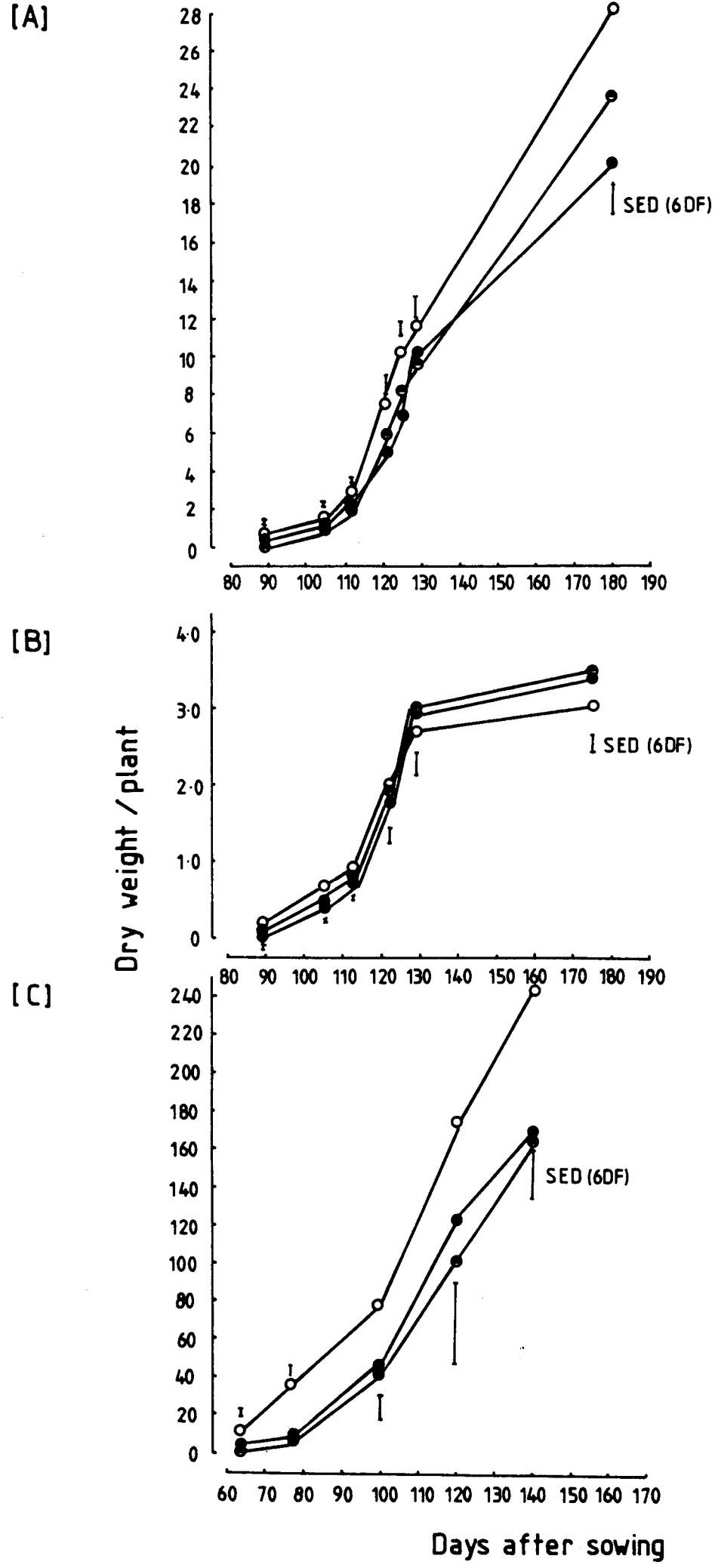

Dry weight [g m^{-2}]
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
SED (6 DF)
60 70 80 90 100 110 120 130 140 150 160 170 180
Days after sowing

Figure 4.3 The total dry matter production per plant of field bean (A), spring barley (B) and sugar beet (C) in 1983, as influenced by control (○), compact (●) and DIHB (◒) treatments


[A]
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
SED (6DF)
80 90 100 110 120 130 140 150 160 170 180 190
[B]
4·0
3·0
2·0
1·0
0
SED (6DF)
80 90 100 110 120 130 140 150 160 170 180 190
Dry weight / plant
[C]
240
220
200
180
160
140
120
100
80
60
40
20
0
SED (6DF)
60 70 80 90 100 110 120 130 140 150 160 170
Days after sowing

of compensatory crop growth in compacted soil was also observed by Dawkins (1982) who reported that vining peas were unable to compensate fully for a low plant population in compacted soil. Hebblethwaite and McGowan (1980) studied the effects of soil compaction on the growth of vining peas and sugar beet. They found that although the low plant density had contributed to the reduced overall yield, the effect could not be accounted for solely by the reduced plant population.

In 1984 measurements of crop dry weight were taken more frequently than in 1983 and the data, when expressed in relation to time (Figure 4.4), supports the pattern of crop development proposed by Monteith (1977). He reported that growth could be represented by two straight lines, one representing the increase in development with time and the other representing the maximum development. Monteith (1977) stated that the two lines defined three phases:

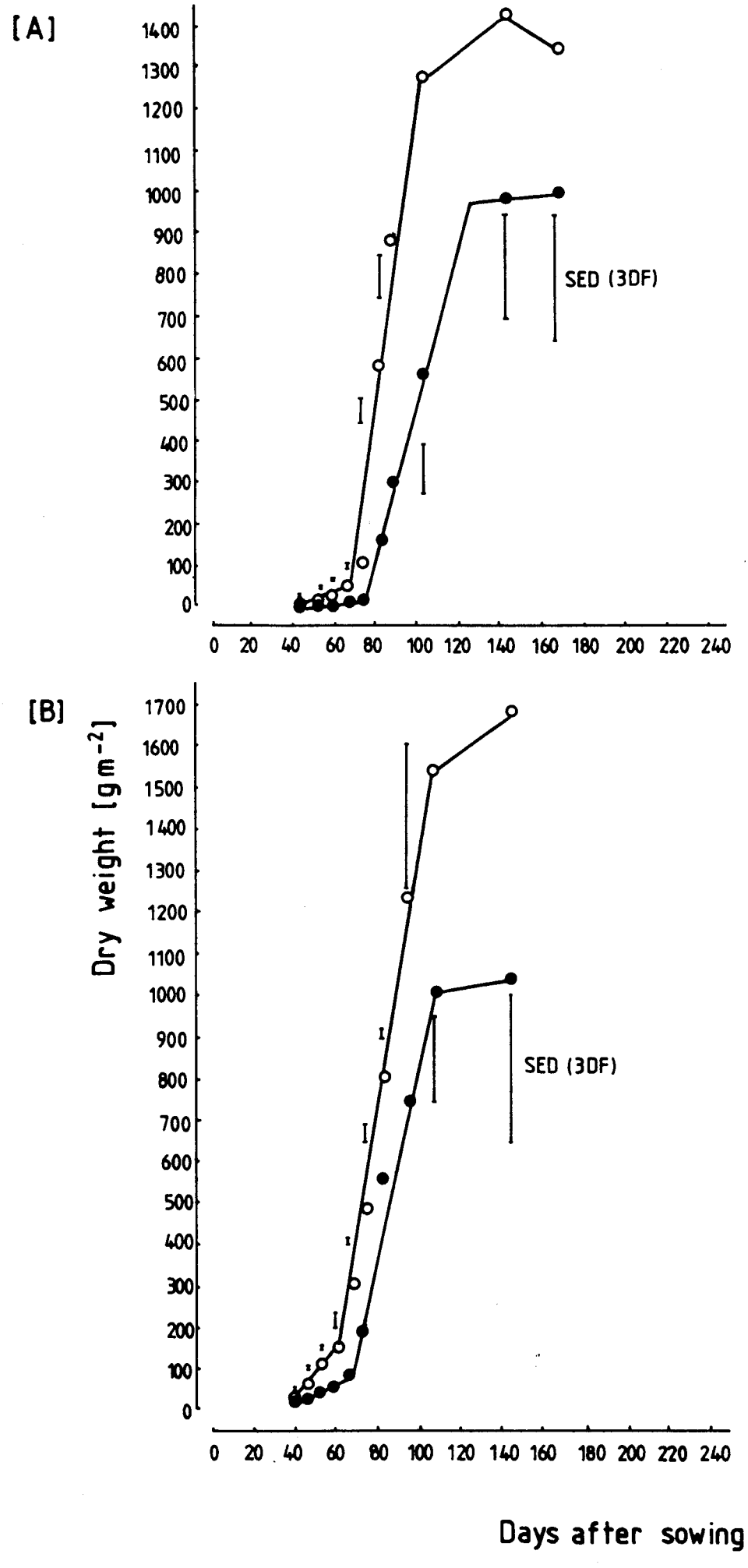
(a) the mean rate of development,

(b) the apparent time that elapses before development starts. A phase described as 'lost time',

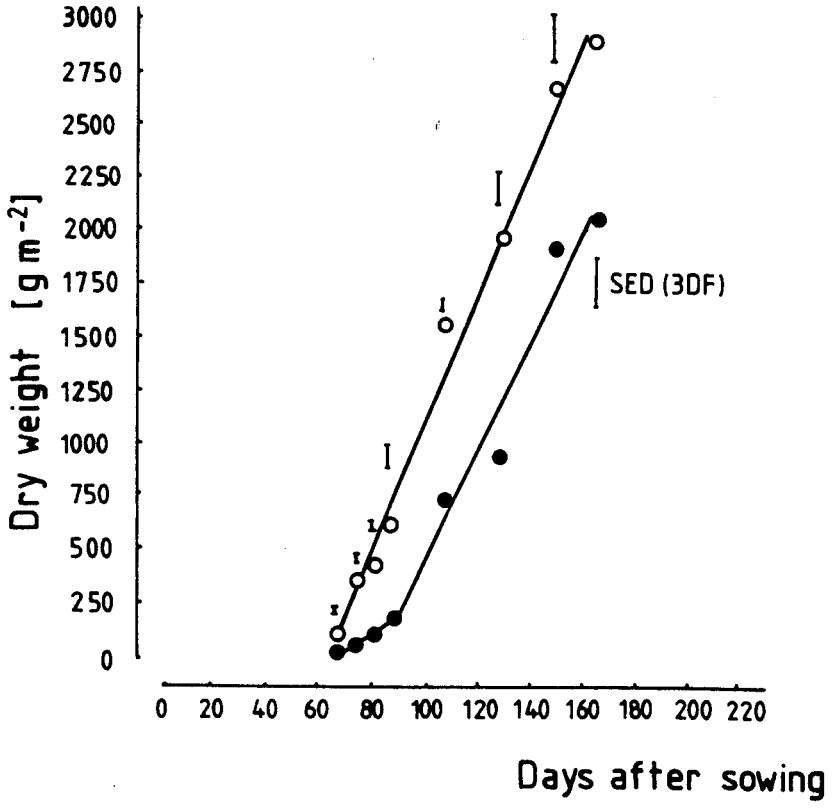
(c) the apparent duration of development.

This pattern of dry matter accumulation was found in the two 'seed' crops — field beans and spring barley. However the 'lost time' phase was found to contain a period of slow initial growth which changed to the main growth phase at a date corresponding to the beginning of stem extension (Green, C. personal communication, 1984). This date was delayed by approximately six days in the compact treatments which suggested that soil compaction prompted a delay in the development of each crop in 1984.

Figure 4.4 The total dry matter production per unit area of field bean (A), spring barley (B) and sugar beet (C) in 1984, as influenced by soil compaction. Control (o); Compact (●)


[A]
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
SED (3DF)
0 20 40 60 80 100 120 140 160 180 200 220 240
[B]
Dry weight [g m^{-2}]
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
SED (3DF)
0 20 40 60 80 100 120 140 160 180 200 220 240
Days after sowing

[C]


3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
Dry weight [g m-2]
SED (3DF)
0 20 40 60 80 100 120 140 160 180 200 220
Days after sowing

The total dry matter accumulation per unit area of field beans, spring barley and sugar beet was reduced by compaction throughout the 1984 season and consequently the maximum total dry matter produced by each compact treatment was lower than the control.

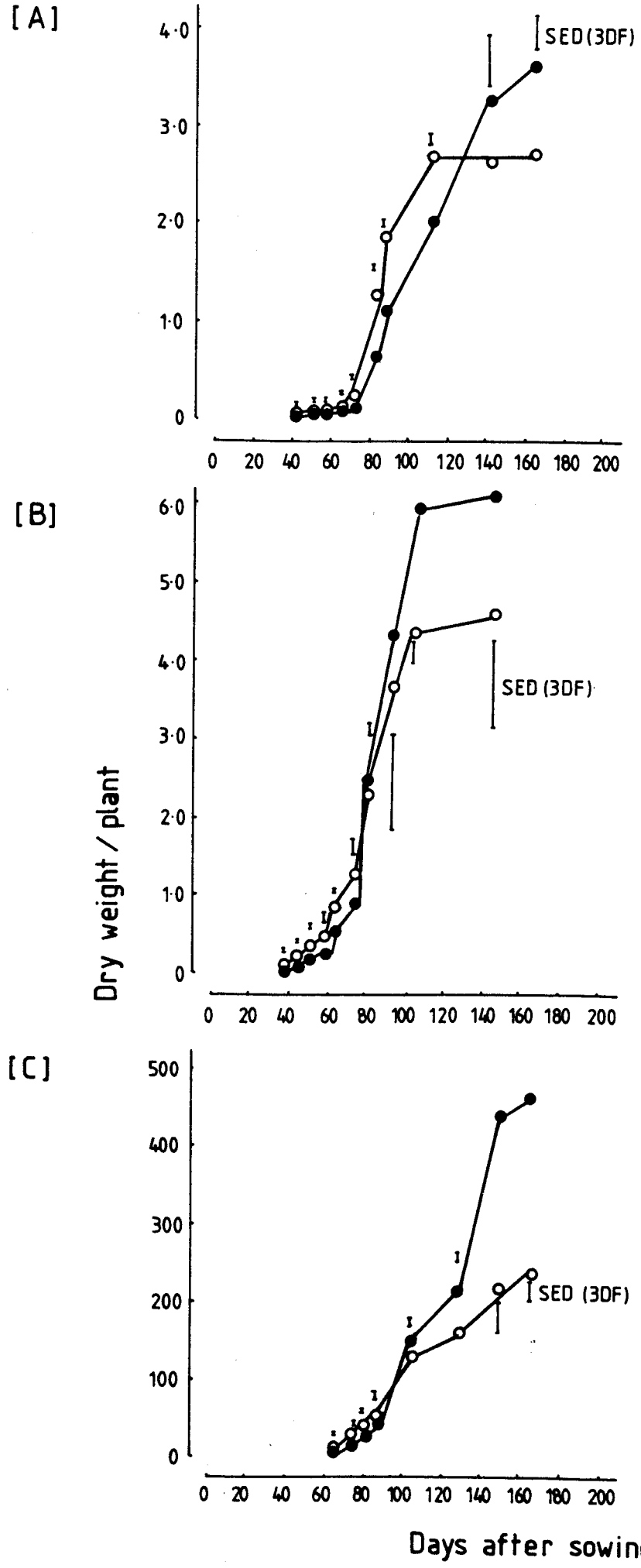
The dry matter accumulation per plant of the three crops was initially reduced by the compact treatment as a result of the delayed emergence. However, in contrast to the 1983 trials, in 1984 each crop quickly compensated for the low population of the compact treatment and at final harvest time the compact plant dry weight was greater than that of the control (Figure 4.5).

Therefore the principal effect of soil compaction on crop growth in 1984 was to reduce the plant population whereas the individual plant performance was indeed improved.

4.3.3 Mineral Analysis of Plant Material

Cooke (1963) reviewed the subject of fertilizer availability to plants and reported that "the value of nutrients, whether from fertilizers or from natural reserves in the soil is affected by physical conditions that alter the chances of contact between roots and nutrients". The effects of compaction on nutrient uptake are related to the volume of soil explored by the roots and to anatomical and morphological changes in the root system. Baligar, Nash, Hare and Price (1975) found that compacting the soil around soybean roots caused wavy root surfaces and thicker casparian strips and secondary cell walls of xylem vessels. Thickening of the cell cortex and casparian strips is thought to have a direct effect on the absorption of some nutrients (Castillo, Dowdy, Bradford and Larson, 1982). In 1984 dry matter samples of each crop were analysed for nutrient content

Figure 4.5 The total dry matter production per plant of field bean (A), spring barley (B) and sugar beet (C) in 1984, as influenced by soil compaction. Control (o); Compact (●)


[A]
4·0
3·0
2·0
1·0
0
SED(3DF)
0 20 40 60 80 100 120 140 160 180 200
[B]
6·0
5·0
4·0
3·0
2·0
1·0
0
SED (3DF)
Dry weight / plant
0 20 40 60 80 100 120 140 160 180 200
[C]
500
400
300
200
100
0
SED (3DF)
0 20 40 60 80 100 120 140 160 180 200
Days after sowing

in order to examine the influence of the compaction treatment on crop nutrient uptake.

The percentage content of nitrogen, phosphorus, potassium, magnesium, calcium and sodium minerals in the shoots of control and compact plants is shown in Table 4.1. In general the content of all nutrients declined over the growing period. At the first harvest, 59 days after sowing, compaction reduced significantly the content of phosphorus and potassium in field bean tissue. This observation was also made by Dawkins (1982) in the vining pea crop and by Gooderham (1973) in the barley and kale crops. However, during the second harvest, 87 days after sowing, the concentrations of nitrogen, magnesium and calcium in the compact treatment were significantly greater than the control, although the potassium content remained significantly reduced by compaction.

In spring barley there was a trend for the content of all minerals to be higher in the compact crop at both harvests although the treatment differences were small.

In the sugar beet crop the concentration of nitrogen was reduced in the compact treatment at the first ($p<0.01$) and second (NS) sampling dates but no other trends were observed.

It is evident that no clear trend evolved which suggested how soil compaction influenced the plant nutrient uptake.

When the mineral content was expressed as uptake per unit area (Figure 4.6), there was a significant reduction in the uptake of all minerals in the compact crops, largely as a result of the reduction in plant population.

Table 4.1 The percentage nutrient content of field beans, spring barley and sugar beet shoots at two harvest dates in 1984

Mineral	Control	Compact	SED	Sig* (3DF)	Control	Compact	SED	Sig* (3DF)
	59 days after sowing				87 days after sowing			
FIELD BEANS								
Nitrogen (N)	4.98	4.69	0.30	NS	2.42	3.69	0.16	$p<0.05$
Phosphorus (P)	0.69	0.60	0.01	$p<0.05$	0.56	0.53	0.01	NS
Potassium (K)	4.50	3.70	0.04	$p<0.01$	4.27	3.74	0.10	$p<0.05$
Magnesium (Mg)	0.34	0.32	0.01	NS	0.17	0.29	0.01	$p<0.01$
Calcium (Ca)	1.41	1.42	0.19	NS	0.65	1.25	0.05	$p<0.01$
Sodium (Na)	0.04	0.04	0.01	NS	0.06	0.04	0.01	NS
SPRING BARLEY								
Nitrogen (N)	4.39	5.08	0.24	NS	1.95	2.28	0.27	NS
Phosphorus (P)	0.64	0.73	0.01	$p<0.05$	0.49	0.52	0.02	NS
Potassium (K)	5.08	4.88	0.26	NS	3.24	3.79	0.33	NS
Magnesium (Mg)	0.20	0.23	0.01	NS	0.10	0.13	0.01	NS
Calcium (Ca)	0.57	0.73	0.03	$p<0.05$	0.32	0.40	0.05	NS
Sodium (Na)	0.05	0.06	0.01	NS	0.03	0.03	0.01	NS
SUGAR BEET								
Nitrogen (N)	3.93	3.73	0.01	$p<0.01$	3.25	3.17	0.14	NS
Phosphorus (P)	0.39	0.43	0.01	NS	0.29	0.27	0.01	NS
Potassium (K)	6.64	6.03	0.36	NS	6.03	6.17	0.38	NS
Magnesium (Mg)	0.92	0.62	0.34	NS	1.03	1.25	0.10	NS
Calcium (Ca)	1.17	1.38	0.05	NS	1.63	1.83	0.11	NS
Sodium (Na)	0.72	0.55	0.05	NS	1.89	1.77	0.35	NS

* level of statistical significance

Figure 4.6 The nutrient uptake per unit area of field bean (A), spring barley (B) and sugar beet (C) in 1984 as influenced by soil compaction. SED (3 DF)

Control treatments:

59 days after sowing

87 days after sowing

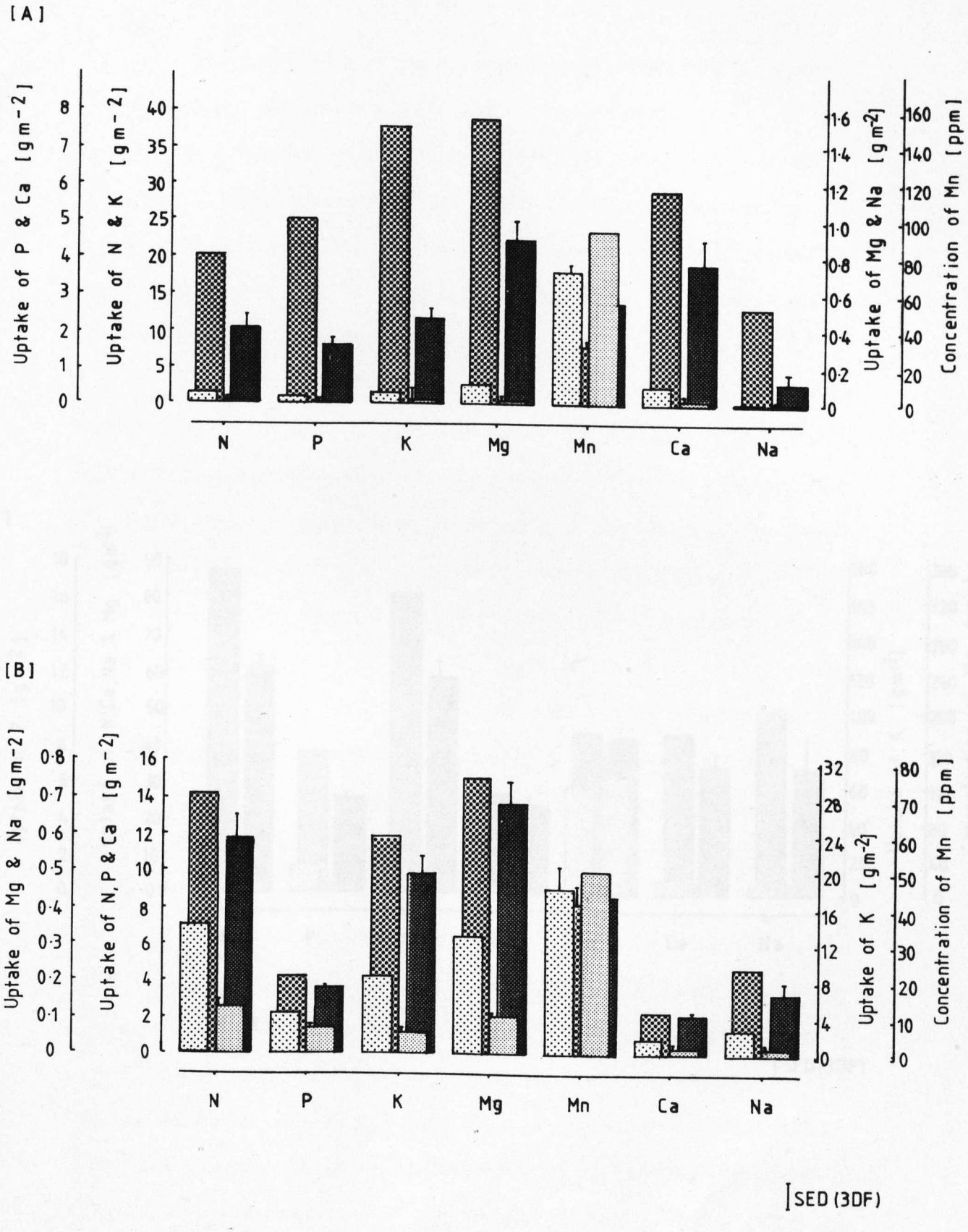
Compact treatents:

59 days after sowing

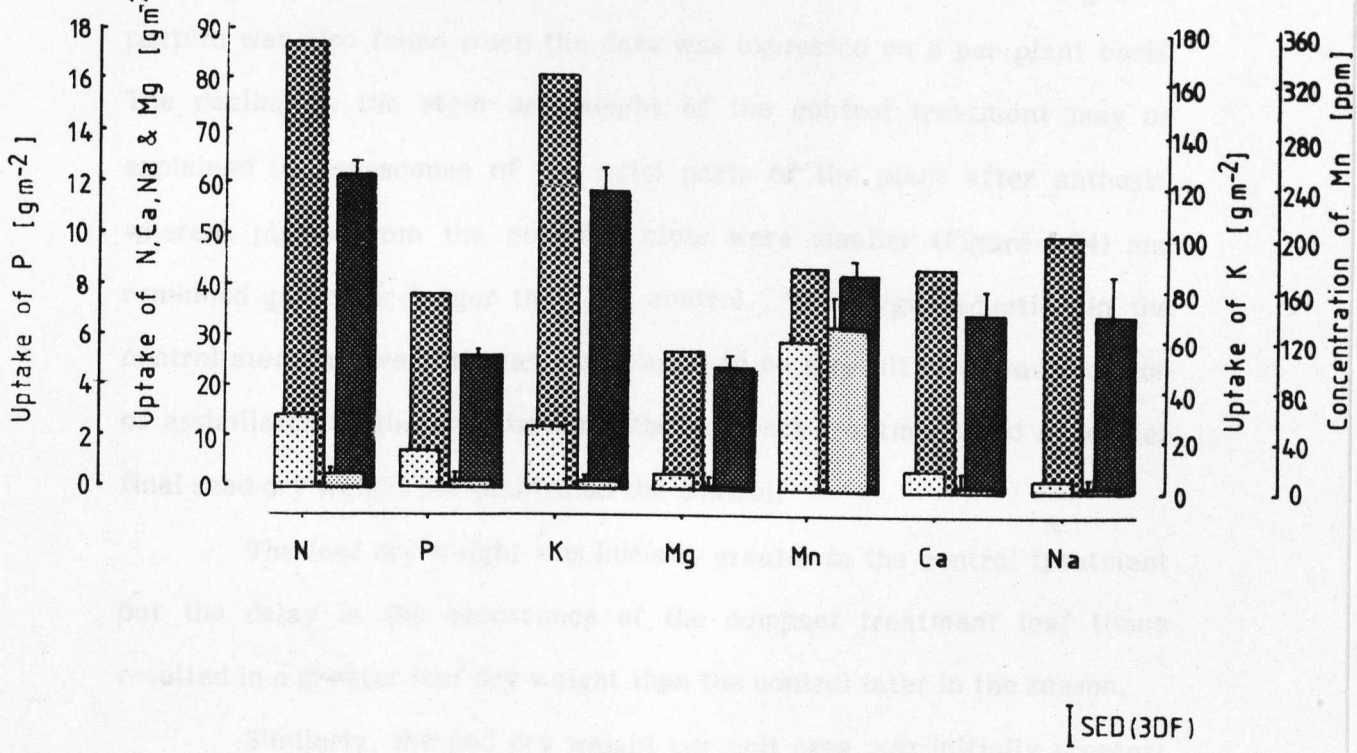
87 days after sowing

Nutrients:

N	=	nitrogen
P	=	phosphorus
K	=	potassium
Mg	=	magnesium
Mn	=	manganese
Ca	=	calcium
Na	=	sodium


[A]
Uptake of P & Ca [g m⁻²]
Uptake of N & K [g m⁻²]
Uptake of Mg & Na [g m⁻²]
Concentration of Mn [ppm]
N
P
K
Mg
Mn
Ca
Na
[B]
Uptake of Mg & Na [g m⁻²]
Uptake of N, P & Ca [g m⁻²]
Uptake of K [g m⁻²]
Concentration of Mn [ppm]
N
P
K
Mg
Mn
Ca
Na
SED (3DF)

[C]


Uptake of P [g m-2]
Uptake of N,Ca,Na & Mg [g m-2]
Uptake of K [g m-2]
Concentration of Mn [ppm]
0
2
4
6
8
10
12
14
16
18
0
10
20
30
40
50
60
70
80
90
0
20
40
60
80
100
120
140
160
180
0
40
80
120
160
200
240
280
320
360
N
P
K
Mg
Mn
Ca
Na
SED(3DF)

4.3.4 Partitioning of Dry Matter

The partitioning of the dry matter production of field beans into leaf, stem, pod and seed in 1984 is shown in Figure 4.7.

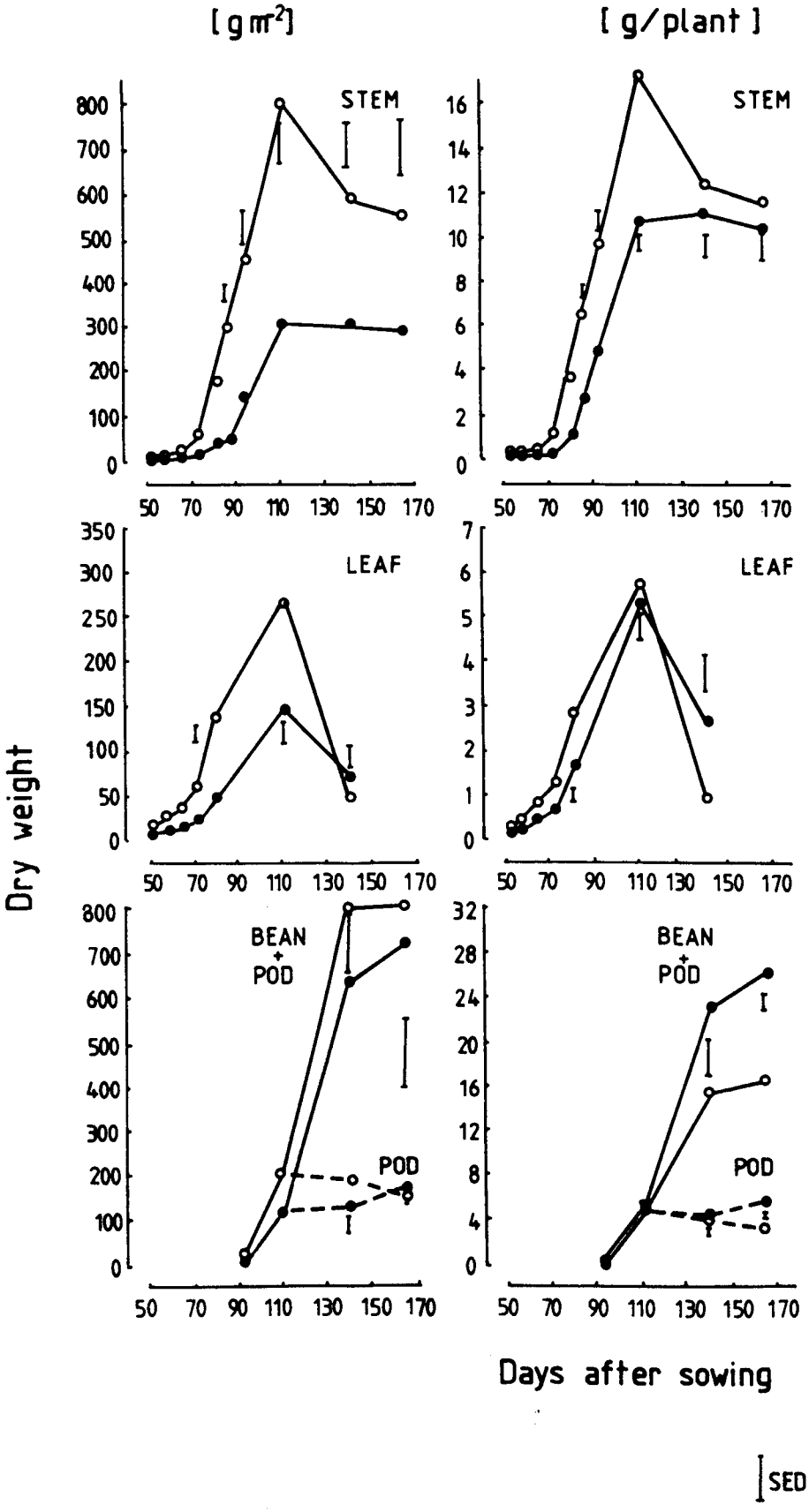
The control crop produced a significantly greater dry weight ($p<0.05$) of all components per unit area until 110 days after sowing. The difference between the treatments diminished towards the end of the season as a result of the compensatory growth of the compact plants, which continued for longer than the control.

The field bean stem achieved a maximum dry weight at 110 days after sowing and this remained constant in the compact treatment until harvest; however the control crop stem dry weight declined sharply after this date which corresponded to the beginning of pod fill. A similar growth pattern was also found when the data was expressed on a per plant basis. The decline in the stem dry weight of the control treatment may be explained by senescence of the axial parts of the plant after anthesis, whereas plants from the compact plots were smaller (Figure 4.14) and remained green for longer than the control. The large reduction in the control stem dry weights was not thought to be a result of retranslocation of assimilates to the seed because the compact treatment had a heavier final seed dry weight per plant than the control.

The leaf dry weight was initially greater in the control treatment but the delay in the senescence of the compact treatment leaf tissue resulted in a greater leaf dry weight than the control later in the season.

Similarly, the pod dry weight per unit area was initially greatest in the control treatment but this difference decreased with time as the compact treatment displayed compensatory growth and the pod and seed dry weight per plant became heavier than the control by final harvest.

Figure 4.7 The effect of soil compaction on the leaf, stem, pod and seed dry weight of field beans in 1984, expressed per unit area and per plant.
Control (o); Compact (●)


[g m²]
[g/plant]
STEM
STEM
LEAF
LEAF
BEAN + POD
BEAN + POD
POD
POD
Dry weight
Days after sowing
SED (3DF)

The leaf, stem and grain dry weight of spring barley in 1984 is shown in Figure 4.8. Soil compaction reduced the stem dry weight per unit area of barley throughout the season. However, in spite of an initial reduction in the stem dry weight per plant, the compact treatment showed a similar compensatory growth to that found in the field bean crop and consequently after mid-June the compact stem dry weight per plant was greater than the control.

The leaf dry weight per unit area was significantly reduced by compaction until maximum dry weight was achieved at 82 days after sowing. The leaves then began to senesce and the difference between the treatments became negligible. The leaf dry weight per plant followed a similar pattern to that of stem dry weight; the initial treatment difference was reversed by compensatory growth of the compact treatment later in the season.

The grain dry weight per unit area was reduced in the compact treatment, but this was probably a result of the low plant population because the grain dry weight of the compact treatment plants was heavier than that of the control at each sampling date.

Soil compaction reduced the dry matter accumulation per unit area of the leaf, petiole, crown and root of the sugar beet crop at every harvest in 1983 (Figure 4.9). This reduction could not be accounted for entirely by a reduced plant population because the dry matter accumulation per plant (Figure 4.10) was also reduced by compaction through the season. Therefore, in 1983, soil compaction impaired the individual plant performance thus preventing its ability to compensate for the low plant population and thus reducing the final root dry weight per plant ($p<0.01$).

Figure 4.8 The effect of soil compaction on the leaf, stem and grain dry weight of spring barley in 1984, expressed per unit area and per plant.
Control (o); Compact (●)

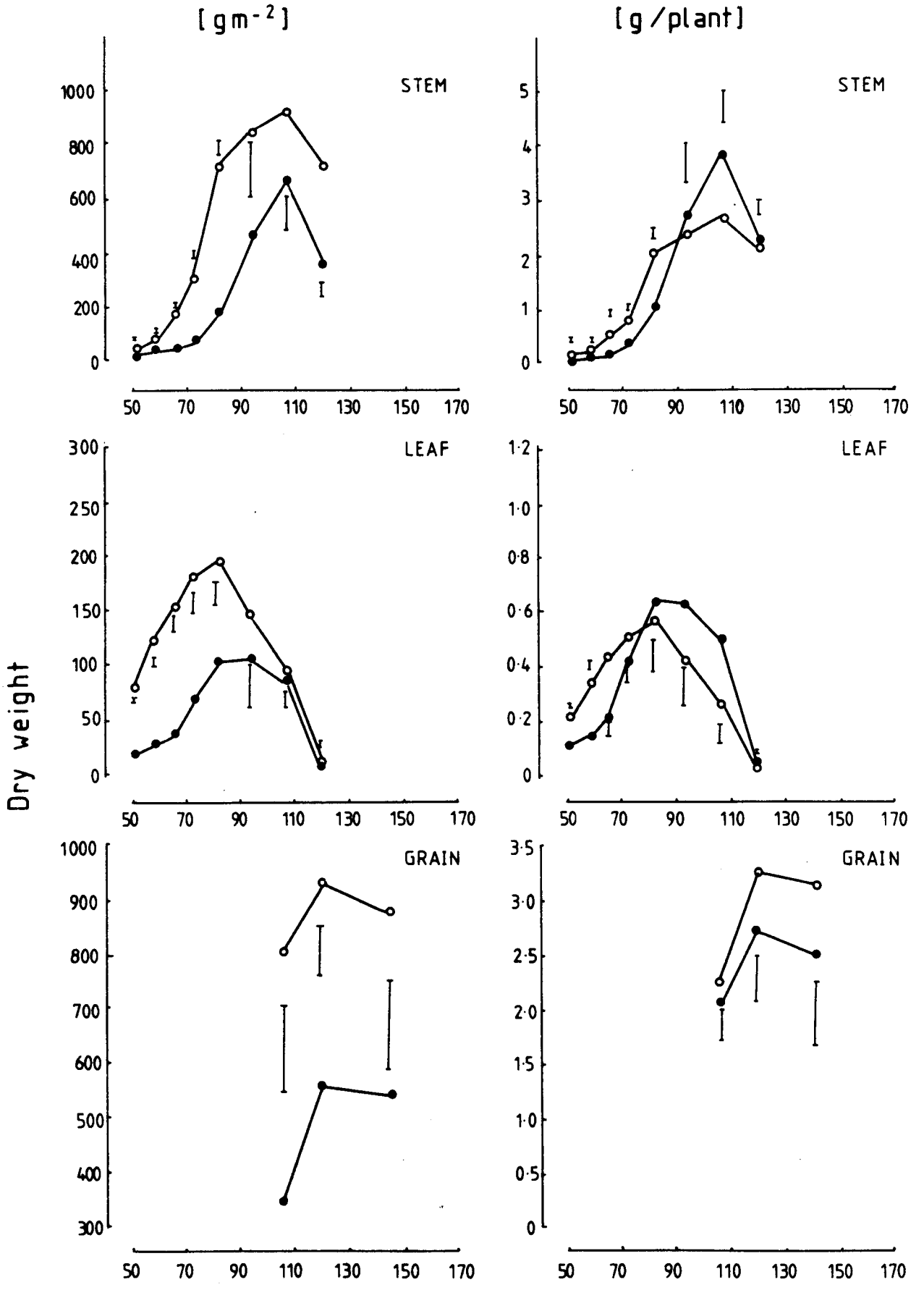

[g m-2]
[g /plant]
STEM
STEM
LEAF
LEAF
GRAIN
GRAIN
Dry weight
Days after sowing
SED (3DF)

Figure 4.9 The effect of soil compaction on the leaf, petiole, crown and root dry weight of per unit area of sugar beet in 1983 (see Appendix 3, Table 1 for statistical analysis)

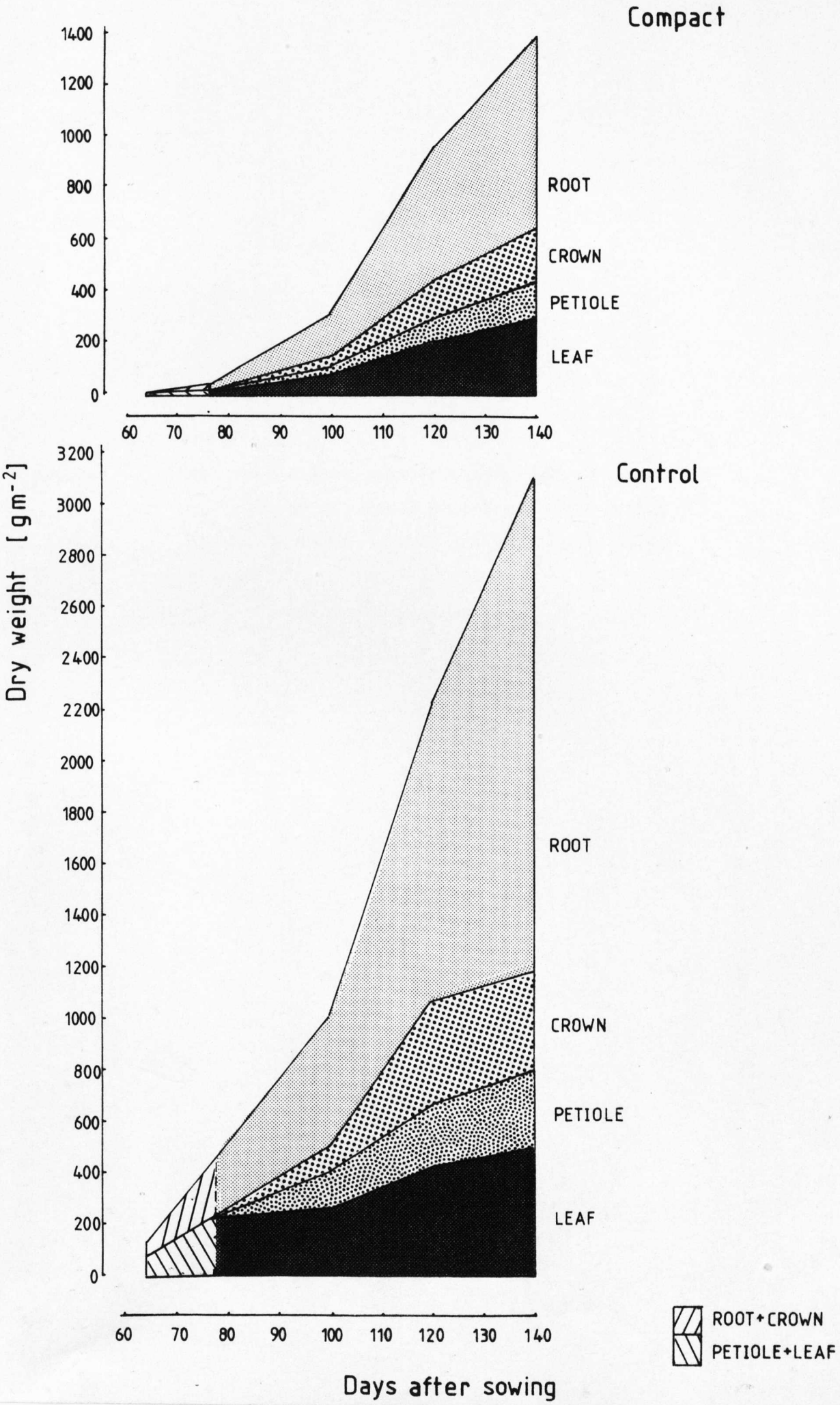
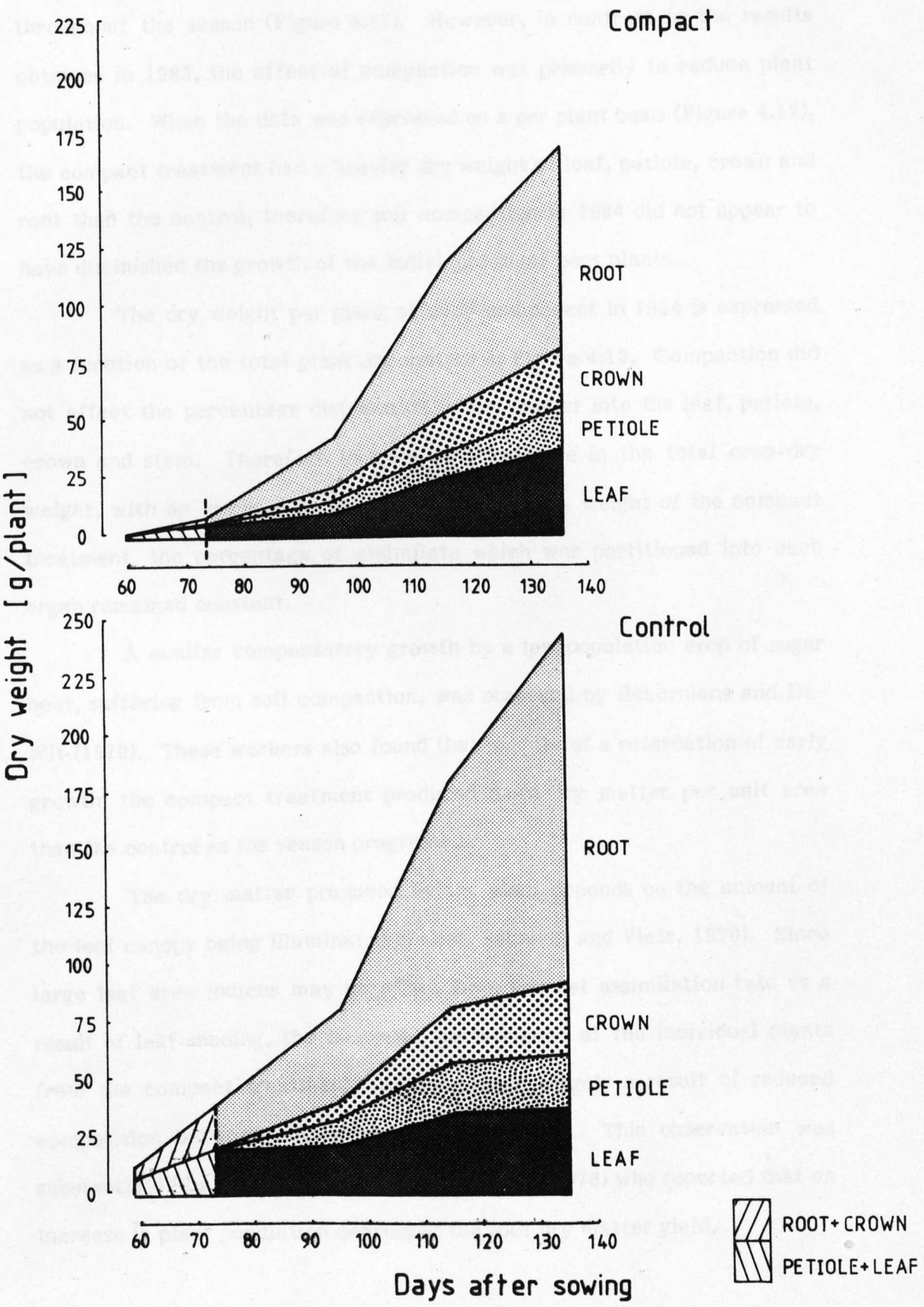

Compact
1400
1200
1000
800
600
400
200
0
ROOT
CROWN
PETIOLE
LEAF
60
70
80
90
100
110
120
130
140
Control
Dry weight [g m-2]
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
ROOT
CROWN
PETIOLE
LEAF
ROOT+CROWN
PETIOLE+LEAF
Days after sowing

Figure 4.10 The effect of soil compaction on the leaf, petiole, crown and root dry weight per plant of sugar beet in 1983 (see Appendix 3, Table 2 for statistical analysis)


Compact
Control
Dry weight [g/plant]
Days after sowing
ROOT
CROWN
PETIOLE
LEAF
ROOT+CROWN
PETIOLE+LEAF
0
25
50
75
100
125
150
175
200
225
250
60
70
80
90
100
110
120
130
140

In 1984, compaction also reduced significantly the dry matter accumulation per unit area of each plant component at every harvest throughout the season (Figure 4.11). However, in contrast to the results obtained in 1983, the effect of compaction was primarily to reduce plant population. When the data was expressed on a per plant basis (Figure 4.12), the compact treatment had a heavier dry weight of leaf, petiole, crown and root than the control, therefore soil compaction in 1984 did not appear to have diminished the growth of the individual sugar beet plants.

The dry weight per plant of each component in 1984 is expressed as a function of the total plant dry matter in Figure 4.13. Compaction did not affect the percentage distribution of dry matter into the leaf, petiole, crown and stem. Therefore in spite of a decrease in the total crop dry weight, with an increase in the individual plant dry weight of the compact treatment, the percentage of assimilate which was partitioned into each organ remained constant.

A similar compensatory growth by a low population crop of sugar beet, suffering from soil compaction, was observed by Bakermans and De-Wit (1970). These workers also found that in spite of a retardation of early growth, the compact treatment produced more dry matter per unit area than the control as the season progressed.

The dry matter produced by the plant depends on the amount of the leaf canopy being illuminated (Follet, Schmehl and Viets, 1970). Since large leaf area indices may be offset by a low net assimilation rate as a result of leaf shading, the increased performance of the individual plants from the compact treatment may have been largely a result of reduced competition between plants for light and water. This observation was substantiated by the work of Scott and Jaggard (1978) who reported that an increase in plant population decreased the root dry matter yield.

Figure 4.11 The effect of soil compaction on the leaf, petiole, crown and root dry weight per unit area of sugar beet in 1984 (see Appendix 3, Table 3 for statistical analysis)

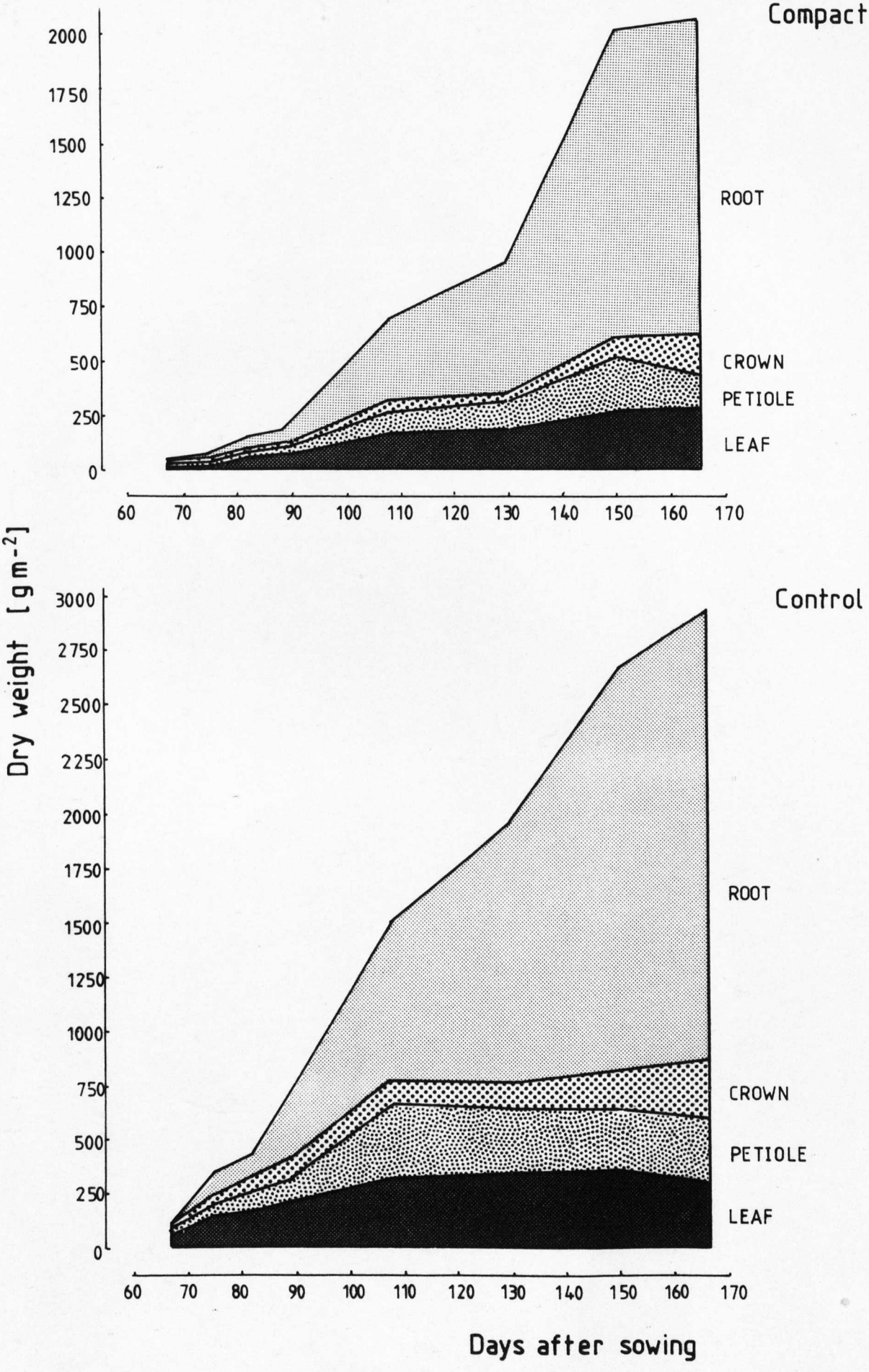

Compact
2000
1750
1500
1250
1000
750
500
250
0
ROOT
CROWN
PETIOLE
LEAF
60
70
80
90
100
110
120
130
140
150
160
170
Dry weight [g m-2]
Control
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
ROOT
CROWN
PETIOLE
LEAF
60
70
80
90
100
110
120
130
140
150
160
170
Days after sowing

Figure 4.12 The effect of soil compaction on the leaf, petiole, crown and root dry weight per plant of sugar beet in 1984 (see Appendix 3, Table 4 for statistical analysis)

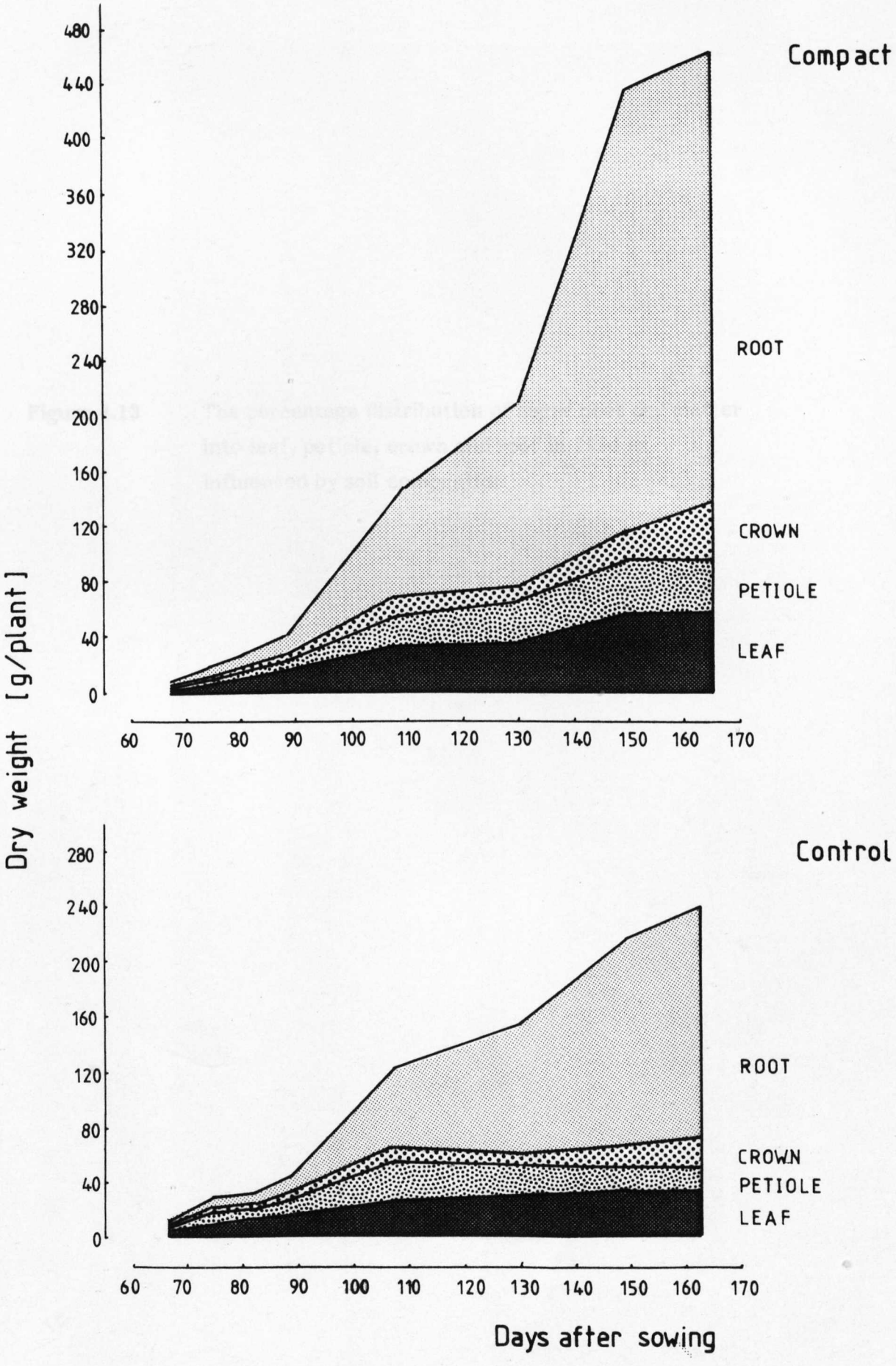
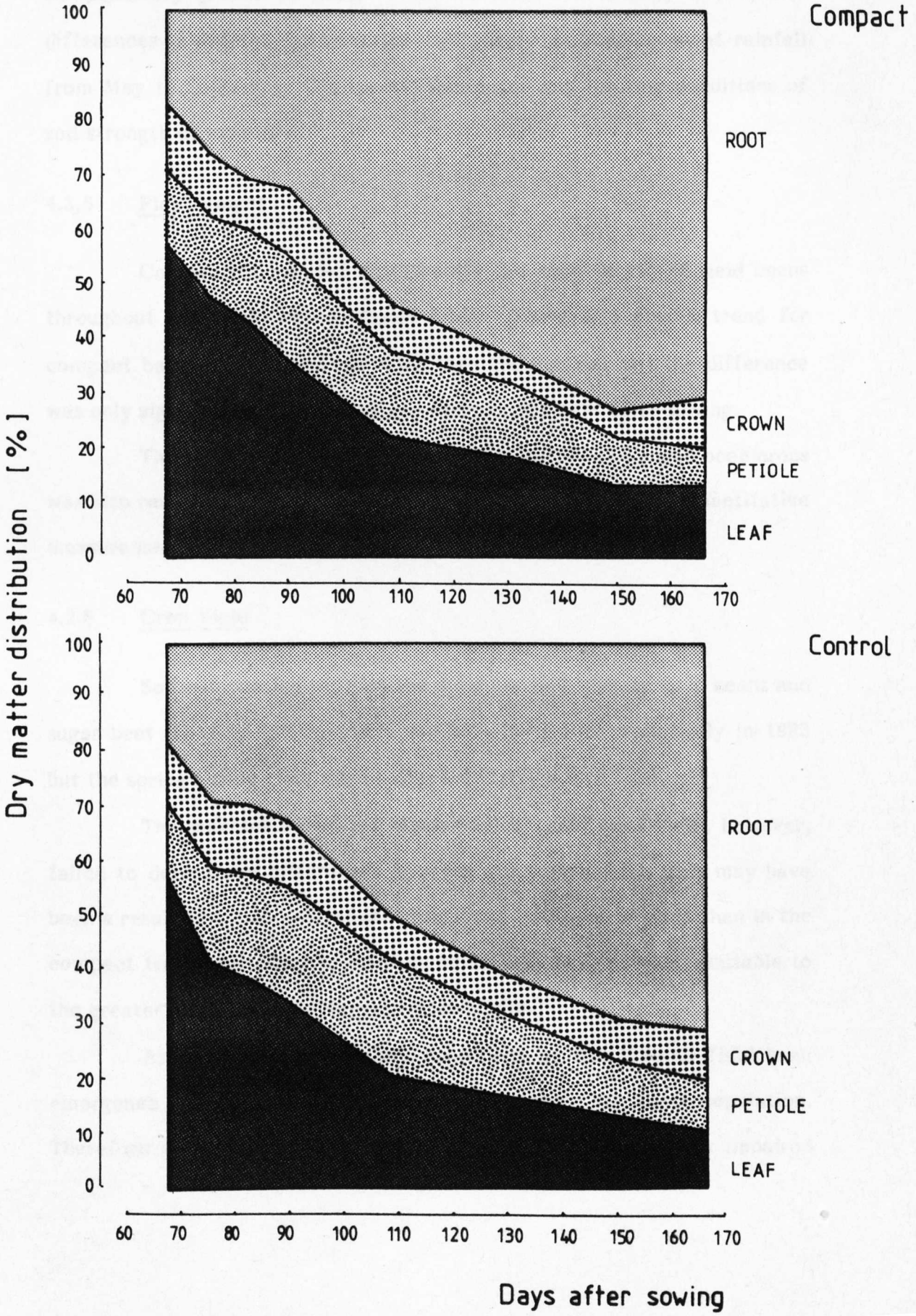

Compact
480
440
400
360
320
280
240
200
160
120
80
40
0
ROOT
CROWN
PETIOLE
LEAF
60 70 80 90 100 110 120 130 140 150 160 170
Dry weight [g/plant]
Control
280
240
200
160
120
80
40
0
ROOT
CROWN
PETIOLE
LEAF
60 70 80 90 100 110 120 130 140 150 160 170
Days after sowing

Figure 4.13 The percentage distribution of sugar beet dry matter into leaf, petiole, crown and root in 1984 as influenced by soil compaction


Compact
Control
ROOT
CROWN
PETIOLE
LEAF
Dry matter distribution [%]
Days after sowing
0
10
20
30
40
50
60
70
80
90
100
60
70
80
90
100
110
120
130
140
150
160
170

It is probable that the ability of the compact treatment to make compensatory growth in 1984, but not in 1983 was chiefly a result of differences in rainfall between the two years. In 1984 frequent rainfall from May to September (Figure 2.1) minimised any limiting conditions of soil strength or moisture.

4.3.5 Plant Height

Compaction reduced significantly the stem length of field beans throughout the 1983 season (Figure 4.14). There was also a trend for compact barley plants to be smaller than the controls but the difference was only significant ($p<0.001$) at one harvest, 122 days after sowing.

The height of the field bean, spring barley and sugar beet crops was also reduced by soil compaction in 1984 (Plate 4.3) but no quantitative measurements were made.

4.3.6 Crop Yield

Soil compaction reduced the yield per unit area of field beans and sugar beet roots by 26% ($p<0.01$) and 59% ($p<0.001$) repectively in 1983 but the spring barley yield was unaffected (Table 4.2).

The machine harvested assessment of field bean yield, however, failed to detect any differences between the treatments. This may have been a result of a 31% greater shedding loss in the control plots than in the compact treatment. Higher shedding losses may have been attributable to the greater height of the non-compacted plants.

As a result of moist soil conditions at the time of field bean emergence in 1983, soil compaction did not reduce the plant population. Therefore the reduction in the yield was a direct result of an impaired

Figure 4.14 The stem length of field beans (A) and spring barley (B) in 1983 as influenced by soil compaction. Control (o); Compact (●)

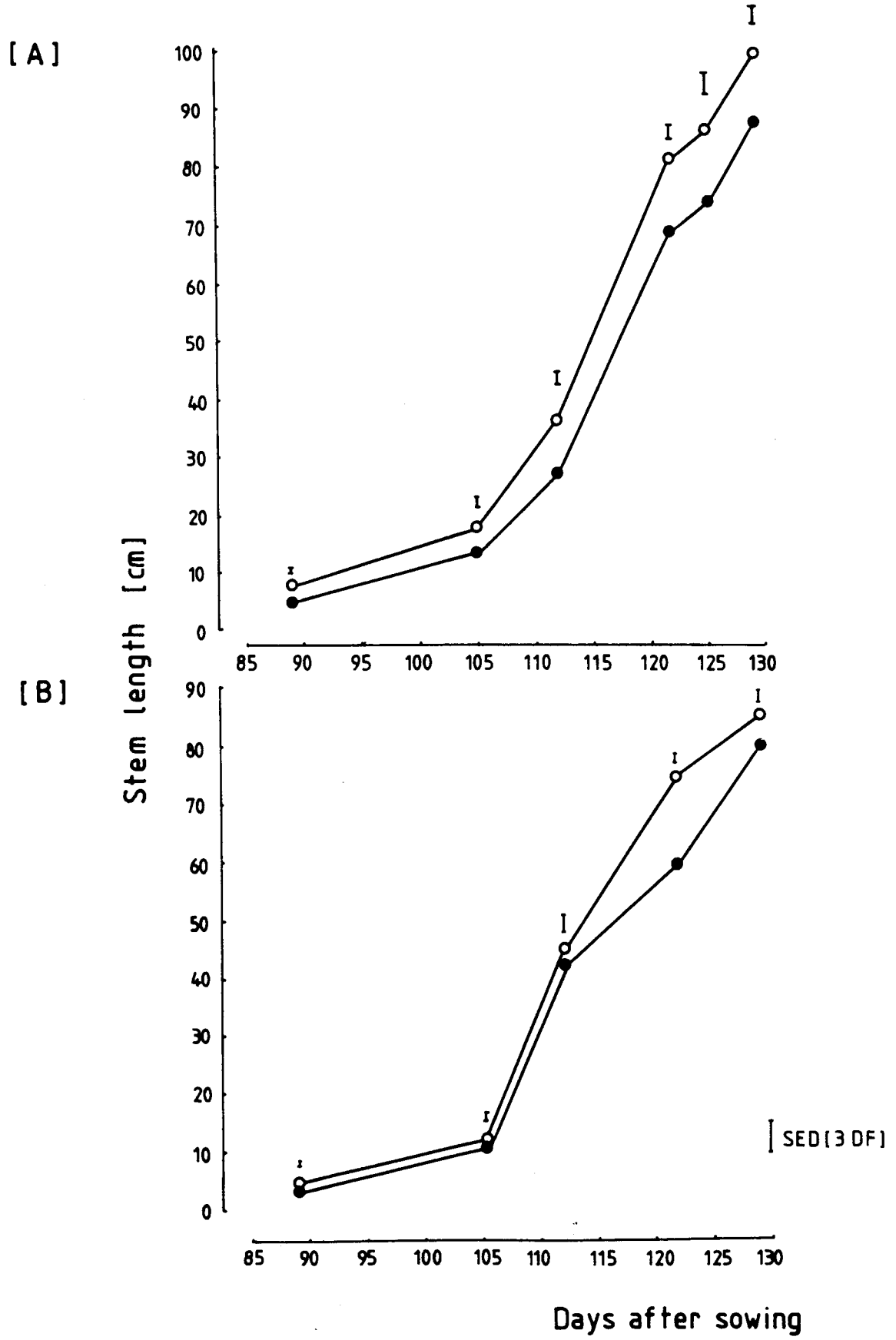

[A]
[B]
Stem length [cm]
Days after sowing
SED [3 DF]
0
10
20
30
40
50
60
70
80
90
100
85
90
95
100
105
110
115
120
125
130

Plate 4.3 The 1984 field trial site showing the large reduction in plant height in the compact treatments

Table 4.2 Yields of field bean, spring barley and sugar beet in 1983

	Control	Compact	DIHB	SED	Sig*	
FIELD BEAN						(6 DF)
Combine yield @ 10% mc (tha^{-1})	2.52	2.83	2.03	0.47	NS	
Growth analysis yield @ 10% mc (gm^{-2})	637.0	471.0	494.0	44.1	$p<0.01$	
Yield plant^{-1} @ 10% mc (g)	17.5	12.6	14.55	0.94	$p<0.01$	
Harvest index	0.56	0.56	0.57	0.01	NS	
SPRING BARLEY						(6 DF)
Combine yield @ 15% mc (tha^{-1})	7.00	7.21	7.40	0.30	NS	
Growth analysis @ 15% mc (gm^{-2})	675.0	678.0	819.0	117.6	NS	
Yield plant^{-1} @ 15% mc (g)	1.86	2.17	2.37	0.33	NS	
Harvest index	0.59	0.65	0.56	0.06	NS	
SUGAR BEET						
Root yield (tha^{-1})	58.10	23.73	21.11	1.63	$p<0.001$	
% sugar content	12.87	12.81	12.98	0.98	NS	
Sugar yield (tha^{-1})	7.42	3.04	2.74	0.50	$p<0.001$	
Dry root weight plant^{-1} (g)	151.9	88.2	89.8	13.9	$p<0.01$	
Harvest index (sugar)	0.07	0.06	0.01	0.01	NS	
Harvest index (root)	0.53	0.45	0.48	0.02	$p<0.05$	
Plants m^{-2}	12.75	8.25	7.50	0.63	$p<0.001$	

mc moisture content

* level of statistical significance

plant performance as indicated by a significantly reduced ($p<0.01$) bean yield per plant of the compact treatment.

This response was also found in the sugar beet crop. In spite of a significantly reduced plant population ($p<0.001$) in the compact treatment, the plants did not display any compensatory growth and the yield per plant was significantly lower ($p<0.01$) than that of the control treatment.

Kubota and Williams (1967) found that compaction of a sandy loam soil by wheeling resulted in a reduction of 45% in the yield of globe beet. Hebblethwaite and McGowan (1980) also quoted a similar yield reduction for sugar beet due to soil compaction and this was attributed to poor root development, preventing full use of soil water and nutrient reserves.

The percentage sugar content of the beet roots was low for both treatments because poor weather in April delayed the sowing of the crop. Compaction had no effect on the percentage sugar content and this result is in accordance with the findings of Draycott, Hull, Messem and Webb (1970) and Jaggard (1977). Blake, Ogden, Adams and Boelter (1960) found that, although compaction had no direct effect on the root sugar content, fanging of the roots (Plate 4.4), which is caused by soil compaction did reduce the percentage sugar content. Fanging was uncommon in 1984 but roots tended to grow out of the soil in response to poor soil structure (Plate 4.5); a condition which would have resulted in a much larger yield reduction if the crop had been harvested with a commercial machine which 'tops' the beet at a fixed height above the ground.

There was found to be no significant effect of the chemical DIHB on the yield of any of the compact treatment crops in 1983.

In 1984 the soil dried out quickly after sowing and plant population was reduced in all crops. Consequently the 'growth analysis'

Plate 4.4 The fanged roots of sugar beet plants grown in compact soil in 1983

Plate 4.5 Sugar beet roots tended to grow out of the soil in response to poor soil structure (1984)

yields of field beans, spring barley and sugar beet were reduced by 11% (NS), 39% (NS) and 34% ($p<0.05$) respectively (Table 4.3).

The percentage sugar content was lower in the roots from the compact treatment but the difference was insignificant. The crop sugar yield was reduced by 3.75 t ha^{-1} ($p<0.05$) by soil compaction owing to a lower ($p<0.05$) crop root weight than the control treatment.

Combine-harvested samples of field beans and spring barley identified significant yield reductions of 35% ($p<0.01$) and 29% ($p<0.001$) respectively. The differences between the yields calculated from combine-harvested samples were probably more significant than the differences between hand-harvested samples because the large harvest area reduced the errors and the variation between replicates. Furthermore as a result of a delayed senescence in the compact treatment, the pods did not shatter to the same degree as those from the control treatment and it is probable that many of the compact plot beans may have passed through the harvester and were therefore not collected.

The yield reduction found in spring barley was much larger in 1984 than in 1983. Other researchers have reported large yield reductions in spring barley as a result of compaction of 75% (Kubota and Williams, 1967) and 45% (Swain, 1981). However Gooderham and Fisher (1975) found that although compaction resulted in restricted plant establishment only consistently small reductions in yield of between zero and 7% were observed.

The crop yield reductions found in the compact treatments in 1984 were largely a result of the reduced plant population because the yield per plant was increased in the compact soil by 37% ($p<0.05$), 18% (NS) and 57% ($p<0.01$) for field beans, spring barley and sugar beet respectively.

Table 4.3 Yields of field bean, spring barley and sugar beet in 1984

	Control	Compact	SED	Sig* (3 DF)
FIELD BEAN				
Combine yield @ 10% mc (tha^{-1})	3.81	2.47	0.30	$p<0.01$
Growth analysis yield @ 10% mc (gm^{-2})	642.0	572.0	156.0	NS
Yield $plant^{-1}$ @ 10% mc (g)	13.17	20.84	1.82	$p<0.05$
Harvest index	0.47	0.57	0.01	$p<0.001$
SPRING BARLEY				
Combine yield @ 15% mc (tha^{-1})	7.38	5.24	0.23	$p<0.001$
Growth analysis @ 15% mc (gm^{-2})	1021.0	627.0	199.0	NS
Yield $plant^{-1}$ @ 15% mc (g)	2.91	3.56	0.67	NS
Harvest index	0.52	0.52	0.06	NS
SUGAR BEET				
Root yield (tha^{-1})	65.0	42.6	5.5	$p<0.05$
% sugar content	15.39	14.67	0.27	NS
Sugar yield (tha^{-1})	10.00	6.25	0.84	$p<0.05$
Dry root weight $plant^{-1}$ (g)	25.6	59.5	4.4	$p<0.01$
Harvest index (sugar)	0.096	0.092	0.001	NS
Harvest index (root)	0.62	0.63	0.01	NS
Plants m^{-2}	12.35	4.45	0.62	$p<0.001$

mc moisture content

* level of statistical significance

Kirby (1967) reported that over a range of plant populations, between 93-800 plants m^{-2}, the crop yield of spring barley only showed a small variation. He also found that a low plant population only failed to compensate when spring sowing was delayed. It is therefore possible that the delay in early growth found in the compact crop was sufficient to prevent complete compensation for the low plant population.

The ratio of grain yield to total dry matter (the harvest index) is not constant for a cereal crop (Green, 1984b) and can be affected if the crop is under stress. Only the root harvest index of sugar beet was reduced significantly ($p<0.05$) by the compaction treatment in 1983 but in 1984 the harvest index of field beans was increased significantly ($p<0.001$) in compact soil.

These results indicate the confusion that exists in the literature concerning the way that stress changes the harvest index of crops. Gallagher, Biscoe, Scott and Dennis-Jones (1977) found that drought caused a reduction in the harvest index of winter wheat crops from 0.45 to 0.37 and Green and Ivins (1984) reported that the disease take-all (Gaeumannomyces graminis) reduced the ratio from 0.43 to 0.27. However the ability of various stress conditions to induce a high allocation of assimilate to reproductive growth has been observed by many workers. Thompson and Taylor (1982) reported that over a 4 year period, crops grown at a lower level of input always produced a higher harvest index than crops grown with minimal constraints to growth. Fasheun and Dennett (1982) also found that good growing conditions resulted in high levels of total dry matter but relatively low seed yield, while Ishag (1973) found that limited vegetative growth was associated with high seed yield and high harvest index.

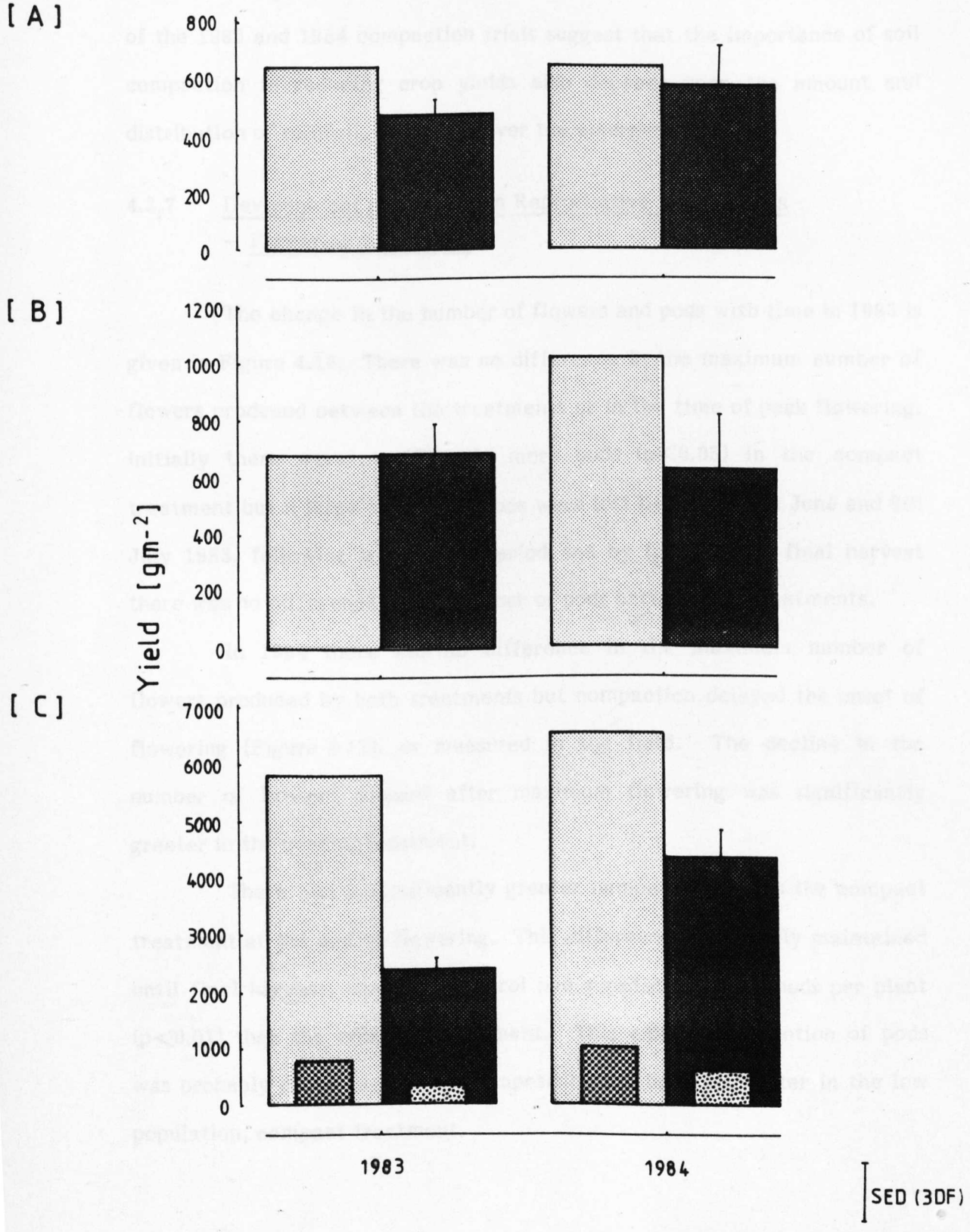
The sensitivity of 'hand-harvested' crop yield to soil compaction differed between 1983 and 1984 (Figure 4.15). El-Karouri and Gooderham (1977) also found the yield response to adverse soil physical conditions varied between seasons. They attributed this variation to differences in the inherent fertility of the soil, the level of applied nitrogenous fertilizer and the distribution of rainfall in relation to the stage of crop growth.

The inherent soil fertility and the levels of applied nitrogenous fertilizer were considered to be similar for the 1983 and 1984 trials and therefore it was only the distribution of rainfall which differed between the two years. The importance of rainfall in the response of crops to soil compaction cannot be overstated. Indeed, Drew and Goss (1971) indicated that the capacity of a root system to absorb nutrients was not impaired when mechanical impedance restricted proliferation, provided that the soil water was plentiful. Dawkins (1982), who investigated the effect of compaction on vining pea production found that reduction in yield varied over three consecutive seasons. He attributed this variation to differences in weather conditions at emergence and to the moisture content of the seedbed at the time of compaction.

Fisher, Gooderham and Ingram (1975) investigated the effects of poor soil physical conditions on the yields of barley and kale. They found that slow early growth of the barley crop in compact soil, probably due to low root activity, was aggravated by dry weather in April and May but the wetter months of June and July allowed compensatory growth. Evans, Wardlaw and Fischer (1975) found that rainfall during June ensured that little water stress occurred after anthesis when the supply of carbon assimilates was known to be important in determining grain yield.

Figure 4.15 The effect of soil compaction on the hand-harvested yield of field beans (A), spring barley (B) and sugar beet (C) in 1983 and 1984. Control ▒; Compact ■.

Sugar beet yield: root - Control ▒; Compact ■
sugar - Control ▒; Compact ▒


[A]
800
600
400
200
0
[B]
1200
1000
800
600
400
200
0
Yield [gm-2]
[C]
7000
6000
5000
4000
3000
2000
1000
0
1983
1984
SED (3DF)
Year

Fisher, Gooderham and Ingram (1975) concluded their paper by stating that the importance of the subsoil to crop yield in a particular season will depend on the amount and distribution of rainfall. The results of the 1983 and 1984 compaction trials suggest that the importance of soil compaction in reducing crop yields also depends upon the amount and distribution of rainfall, especially over the emergence period.

4.3.7 Development of Field Bean Reproductive Components — Flowering to Harvest

The change in the number of flowers and pods with time in 1983 is given in Figure 4.16. There was no difference in the maximum number of flowers produced between the treatments or in the time of peak flowering. Initially there were significantly more pods ($p<0.05$) in the compact treatment but a large number of pods were lost between 20th June and 9th July 1983, following a long dry period and by the time of final harvest there was no difference in the number of pods between the treatments.

In 1984 there was no difference in the maximum number of flowers produced by both treatments but compaction delayed the onset of flowering (Figure 4.17), as measured in the field. The decline in the number of flowers present after maximum flowering was significantly greater in the control treatment.

There was a significantly greater number of pods in the compact treatment at the end of flowering. This difference was largely maintained until final harvest, when the control had significantly less pods per plant ($p<0.01$) than the compact treatment. This enhanced retention of pods was probably due to a reduced competition for light and water in the low population, compact treatment.

Figure 4.16 The influence of soil compaction on the number of field bean flowers and pods per plant in 1983

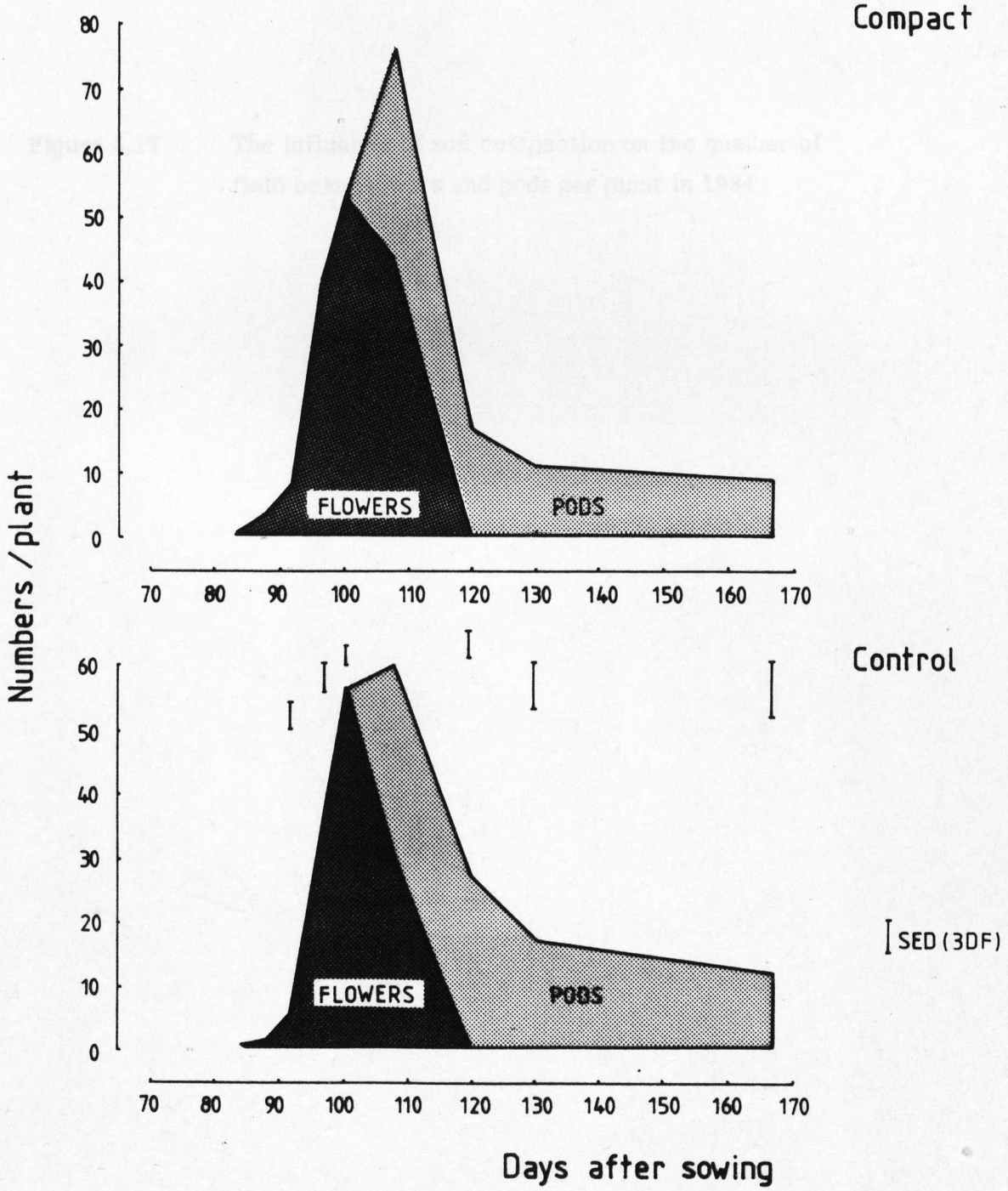
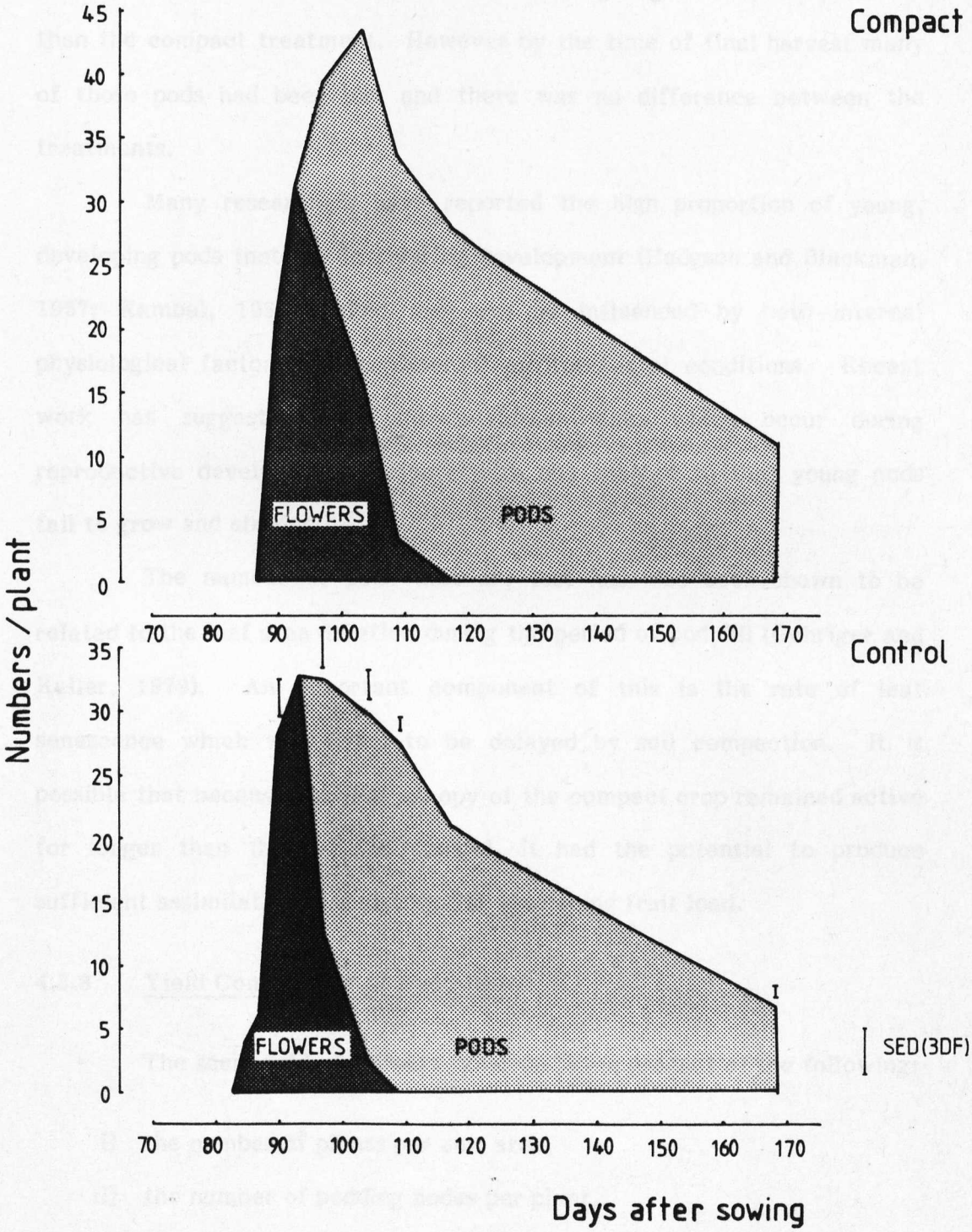

Compact
Control
Numbers / plant
FLOWERS
PODS
FLOWERS
PODS
SED (3DF)
Days after sowing

Figure 4.17 The influence of soil compaction on the number of field bean flowers and pods per plant in 1984


Compact
Control
FLOWERS
PODS
FLOWERS
PODS
Numbers / plant
Days after sowing
SED(3DF)
0
5
10
15
20
25
30
35
40
45
70
80
90
100
110
120
130
140
150
160
170

The number of buds, flowers and pods produced per unit area in 1984, as calculated from growth analysis samples in the laboratory, is given in Figure 4.18. A greater number of flowers and pods was initially produced by the control crop, thus establishing a greater yield potential than the compact treatment. However by the time of final harvest many of those pods had been lost and there was no difference between the treatments.

Many researchers have reported the high proportion of young, developing pods that are lost during development (Hodgson and Blackman, 1957; Kambal, 1969). Pod loss can be influenced by both internal physiological factors and by external environmental conditions. Recent work has suggested that the numerous sinks which occur during reproductive development compete with one another so that young pods fail to grow and abscind.

The number of pods that are lost has also been shown to be related to the leaf area duration during the period of pod fill (Gehriger and Keller, 1979). An important component of this is the rate of leaf senescence which was found to be delayed by soil compaction. It is possible that because the leaf canopy of the compact crop remained active for longer than that of the control, it had the potential to produce sufficient assimilation to maintain the developing fruit load.

4.3.8 Yield Components of Field Bean

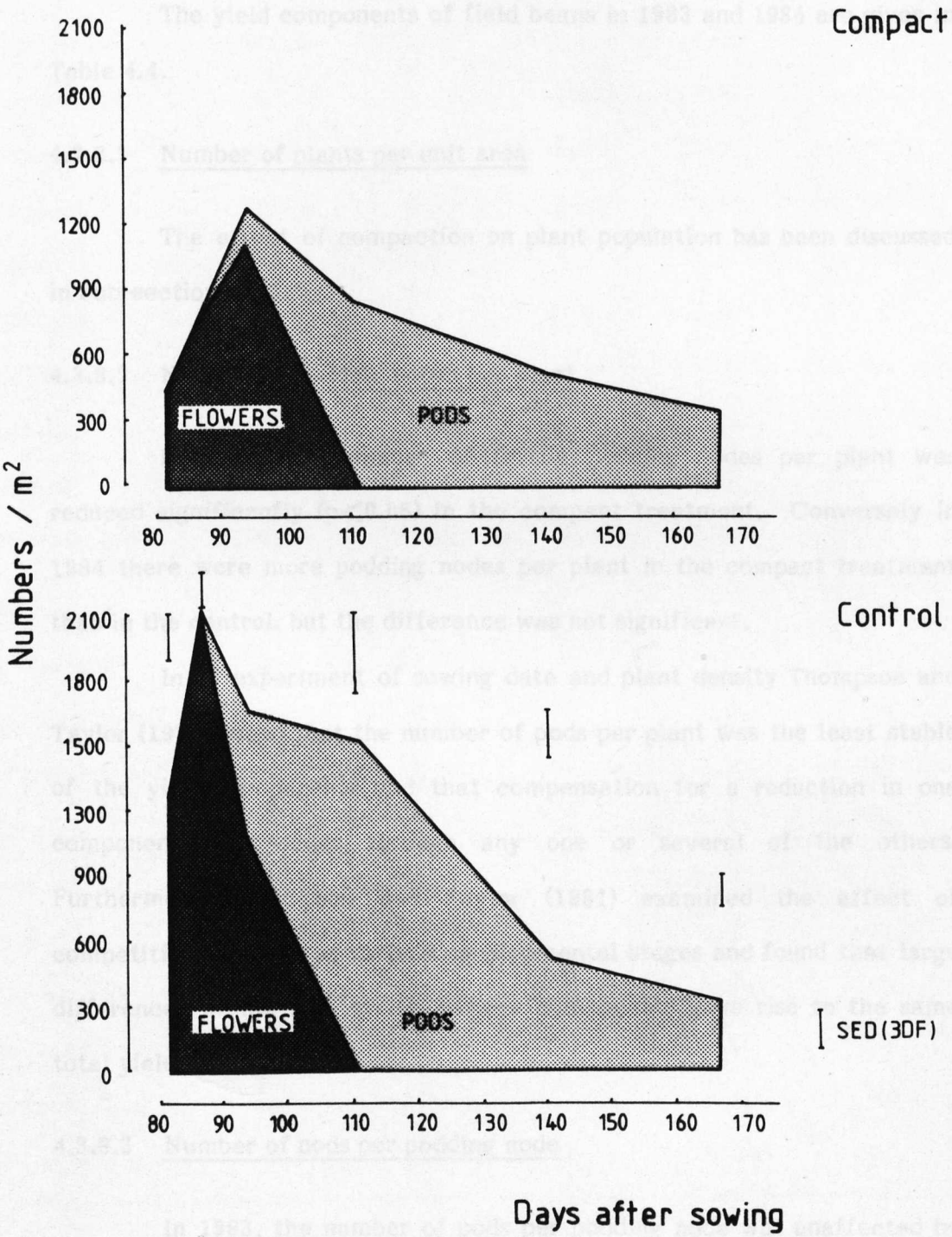
The seed yield of a field bean crop is the product of the following:

i) the number of plants per unit area,

ii) the number of podding nodes per plant,

iii) the number of pods per podding node,

Figure 4.18 The influence of soil compaction on the number of field bean flowers and pods per unit area in 1984


Compact
Control
Numbers / m²
2100
1800
1500
1200
900
600
300
0
1300
FLOWERS
PODS
80
90
100
110
120
130
140
150
160
170
SED(3DF)
Days after sowing

iv) the number of seeds per pod and,

v) the average seed weight (Ishag, 1973; Kambal, 1969; Thompson and Taylor, 1977).

The yield components of field beans in 1983 and 1984 are given in Table 4.4.

4.3.8.1 Number of plants per unit area

The effect of compaction on plant population has been discussed in Sub-section 4.3.1.

4.3.8.2 Number of podding nodes per plant

In 1983, the number of fertile podding nodes per plant was reduced significantly ($p<0.05$) in the compact treatment. Conversely in 1984 there were more podding nodes per plant in the compact treatment than in the control, but the difference was not significant.

In an experiment of sowing date and plant density Thompson and Taylor (1977) found that the number of pods per plant was the least stable of the yield components and that compensation for a reduction in one component may occur through any one or several of the others. Furthermore, Thompson and Taylor (1981) examined the effect of competition for light at various developmental stages and found that large differences in the size of the various components gave rise to the same total yield.

4.3.8.3 Number of pods per podding node

In 1983, the number of pods per podding node was unaffected by soil compaction but in 1984 the compact treatment generated significantly

Table 4.4 Yield components of field beans

	Control	Compact	DIHB	SED	Sig* (6 DF)
1983					
Pod nodes m^{-2}	183.40	147.10	147.00	16.16	NS
Pod nodes $plant^{-1}$	4.97	3.90	4.32	0.30	$p<0.05$
Pod number m^{-2}	462.0	375.0	36.5	35.1	$p<0.05$
Pods $plant^{-1}$	12.65	9.92	10.70	0.68	NS
Seeds m^{-2}	1849.0	1418.0	144.5	123.0	$p<0.01$
Seeds $plant^{-1}$	51.1	38.1	42.6	4.5	NS
Pods per pod node	2.54	2.54	2.47	0.20	NS
Seeds pod^{-1}	4.1	3.9	4.1	0.4	NS
Plants m^{-2}	37.0	37.8	34.0	2.9	NS
Seed weight (g)	0.30	0.29	0.30	0.03	NS
1984					(3 DF)
Pod nodes m^{-2}	193.0	155.0	-	37.4	NS
Pod nodes $plant^{-1}$	4.05	5.62	-	0.55	NS
Pod number m^{-2}	338.38	341.55	-	3.79	NS
Pods $plant^{-1}$	9.36	11.49	-	0.97	NS
Seeds m^{-2}	1658.0	1539.0	-	433.9	NS
Seeds $plant^{-1}$	33.9	55.9	-	5.2	$p<0.05$
Pods per pod node	1.028	1.762	-	0.123	$p<0.01$
Seeds pod^{-1}	4.9	4.5	-	0.5	NS
Plants m^{-2}	47.5	27.8	-	7.1	NS
Seed weight (g)	0.389	0.372	-	0.006	NS

* level of statistical significance

more pods per podding node ($p<0.01$) than the control. At the beginning of pod fill, approximately 94 days after sowing, the control plants had more pods per podding node ($p<0.01$), but as the season progressed the compact treatment lost fewer pods than the control (Figure 4.19) and consequently at harvest, there were more pods per podding node in the compact plots.

4.3.8.4 Number of seeds per pod

There was no difference in the number of seeds per pod in either year. This was to be expected, because for any given cultivar the average number of seeds per pod is relatively stable (Chapman, 1981). Even under conditions of high competition for light, the seed number was found to be the most consistent component of yield (Thompson and Taylor, 1981).

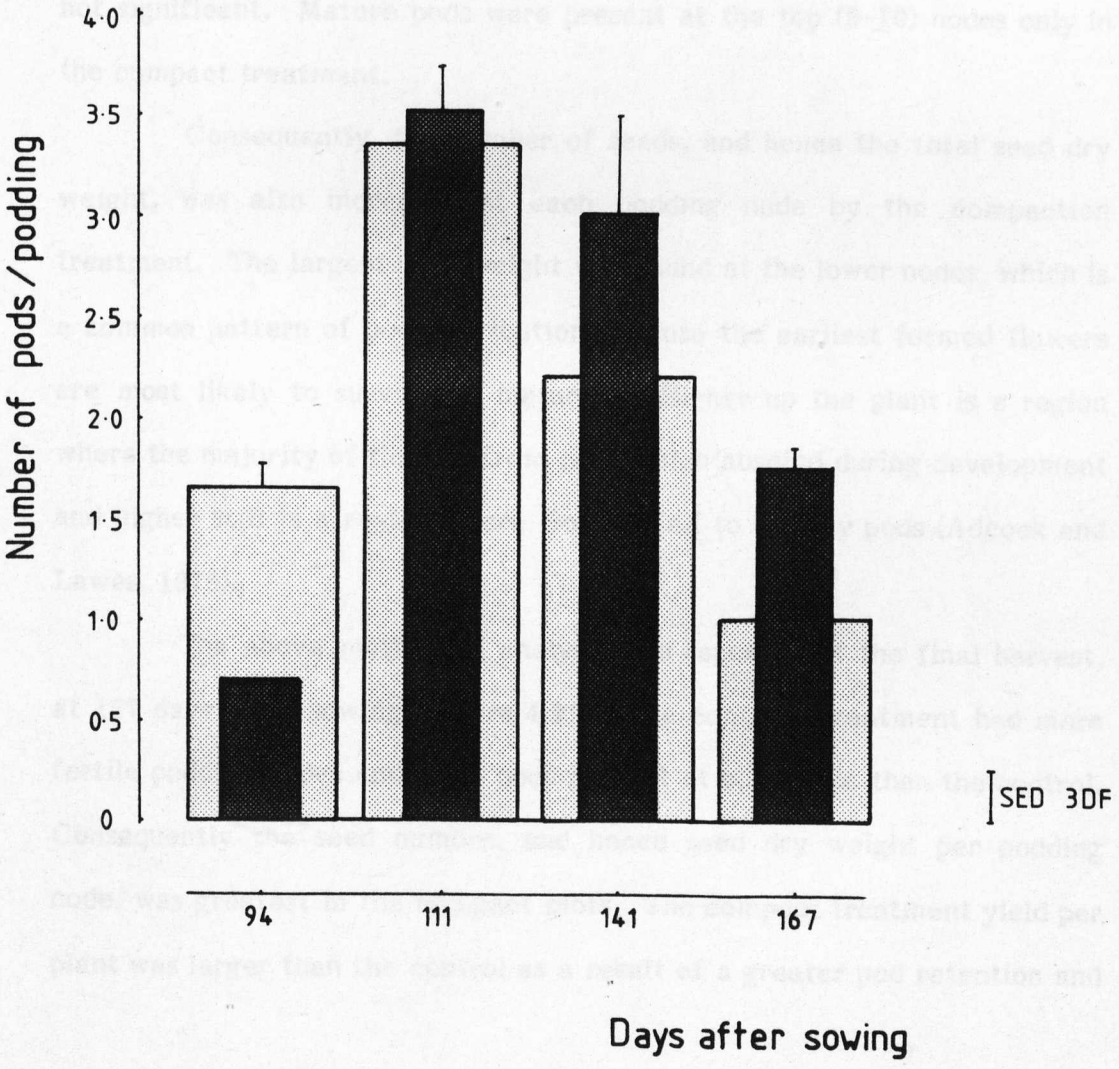
4.3.8.5 Mean seed weight

There was no difference in the mean seed weight in 1983 or 1984.

The results suggest that the yield reduction as a result of compaction, recorded by growth analysis in 1983, was due to a reduced number of podding nodes per plant and consequently fewer pods and therefore seeds per unit area. The DIHB soil treatment did not alleviate the detrimental effect of compaction on the yield components of field beans.

In 1984 the increased yield per plant was attributable to a combination of a greater number of podding nodes per plant (NS) and of more pods per podding node ($p<0.01$) in the compact treatment. It is possible that this was a direct result of the reduced competition for light as a result of the low plant population in the compact plots. Similarly, Ishag (1973) found that there were 40% more pods per plant and the yield

Figure 4.19 The influence of soil compaction on the number of field bean pods pods per podding node in 1984
Control ▒; Compact ■


4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0
Number of pods/podding
SED 3DF
94
111
141
167
Days after sowing

per plant increased by 80% when plants were grown at a low density of 30 plants per m^2 in comparison with those grown at a high density of 58 plants per m^2, but the dense population had 30% higher yield.

4.3.9 Yield Components of Field Bean per Podding Node in 1984

The distribution of mature and immature pods, seed dry weight and seed number on the field bean plant at 118 days after sowing, is given in Figure 4.20.

The compact plants had a greater number of mature and immature pods than the control at each node although the difference was not significant. Mature pods were present at the top (8-10) nodes only in the compact treatment.

Consequently, the number of seeds, and hence the total seed dry weight, was also increased at each podding node by the compaction treatment. The largest seed weight was found at the lower nodes, which is a common pattern of pod distribution because the earliest formed flowers are most likely to survive to maturity. Higher up the plant is a region where the majority of flowers from pods which abscind during development and higher still is a region where flowers fail to set any pods (Adcock and Lawes, 1976).

The above method of analysis was repeated at the final harvest, at 167 days after sowing (Figure 4.21). The compact treatment had more fertile podding nodes and more pods present at each node than the control. Consequently the seed number, and hence seed dry weight per podding node, was greatest in the compact plots. The compact treatment yield per plant was larger than the control as a result of a greater pod retention and

Figure 4.20 The distribution of mature and immature pods, seed dry weight and seed number on the field bean plant at 118 days after sowing in 1984, as influenced by soil compaction. Control ▒; Compact ■
(fertile podding node number 1 refers to the first fertile podding node above the ground)

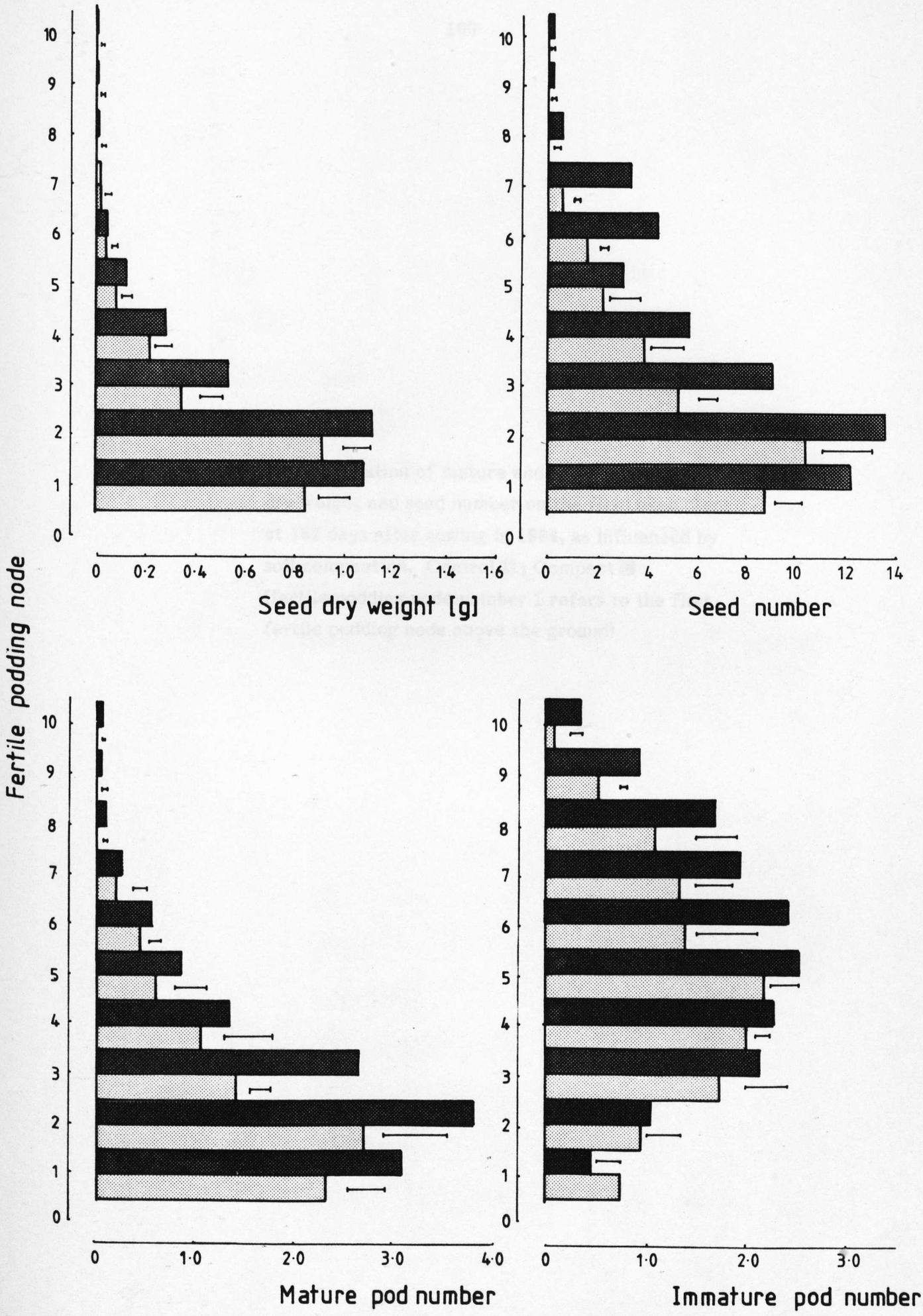
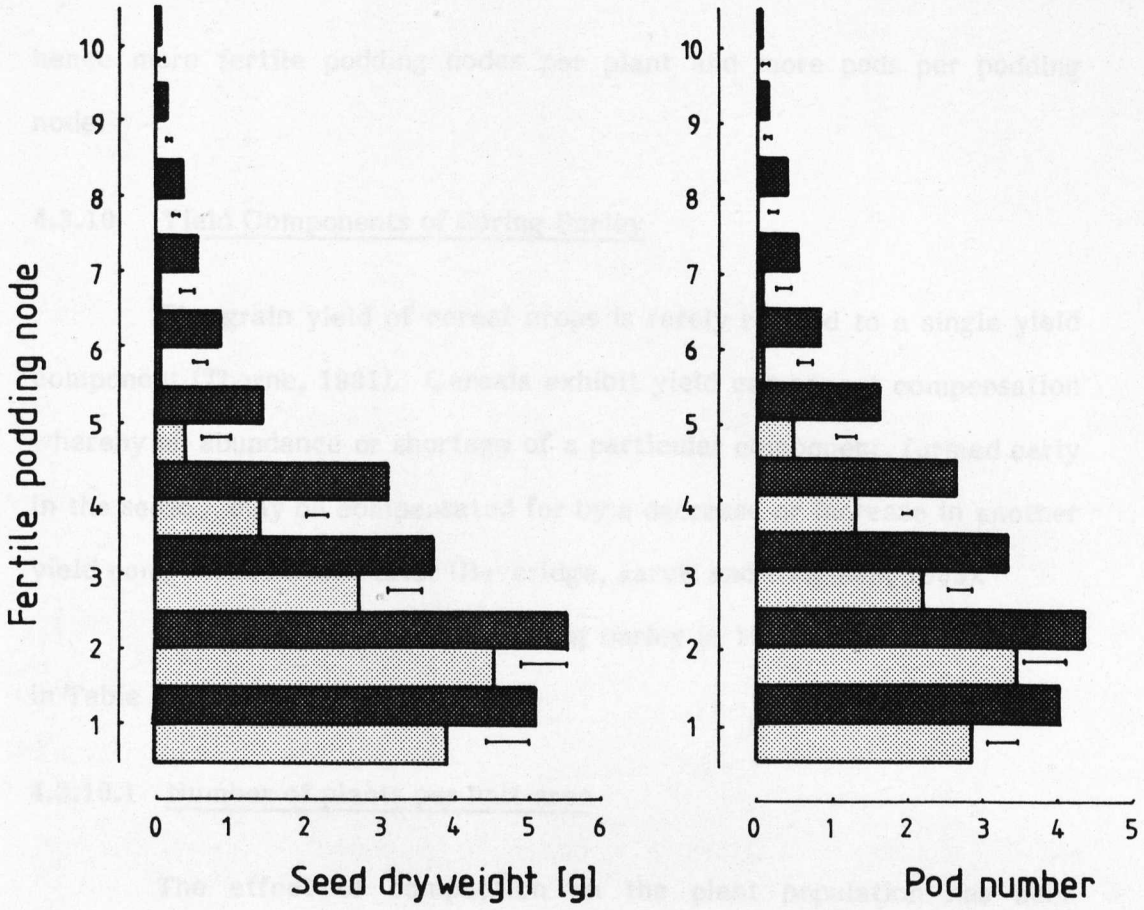
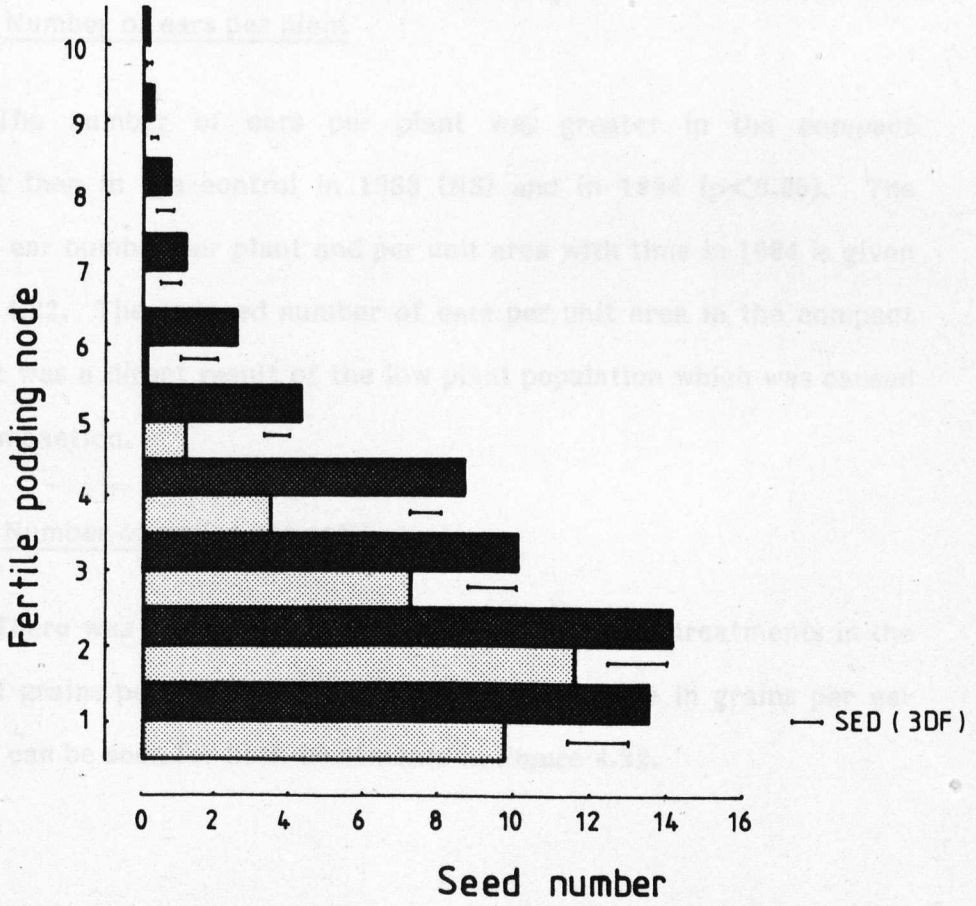

Fertile podding node
Seed dry weight [g]
Seed number
Mature pod number
Immature pod number

Figure 4.21 The distribution of mature and immature pods, seed dry weight and seed number on the field bean plant at 167 days after sowing in 1984, as influenced by soil compaction. Control ▒; Compact ■
(fertile podding node number 1 refers to the first fertile podding node above the ground)


Fertile podding node
10
9
8
7
6
5
4
3
2
1
0 1 2 3 4 5 6
Seed dry weight [g]
0 1 2 3 4 5
Pod number


Fertile podding node
10
9
8
7
6
5
4
3
2
1
0 2 4 6 8 10 12 14 16
Seed number
SED (3DF)

hence more fertile podding nodes per plant and more pods per podding node.

4.3.10 Yield Components of Spring Barley

The grain yield of cereal crops is rarely related to a single yield component (Thorne, 1981). Cereals exhibit yield component compensation whereby an abundance or shortage of a particular component, formed early in the season, may be compensated for by a decrease or increase in another yield component formed later (Beveridge, Jarvis and Ridgman, 1965).

The yield components of spring barley in 1983 and 1984 are shown in Table 4.5.

4.3.10.1 Number of plants per unit area

The effect of compaction on the plant population has been discussed in Sub-section 4.3.1.

4.3.10.2 Number of ears per plant

The number of ears per plant was greater in the compact treatment than in the control in 1983 (NS) and in 1984 ($p<0.05$). The change in ear number per plant and per unit area with time in 1984 is given in Figure 4.22. The reduced number of ears per unit area in the compact treatment was a direct result of the low plant population which was caused by soil compaction.

4.3.10.3 Number of grains per ear

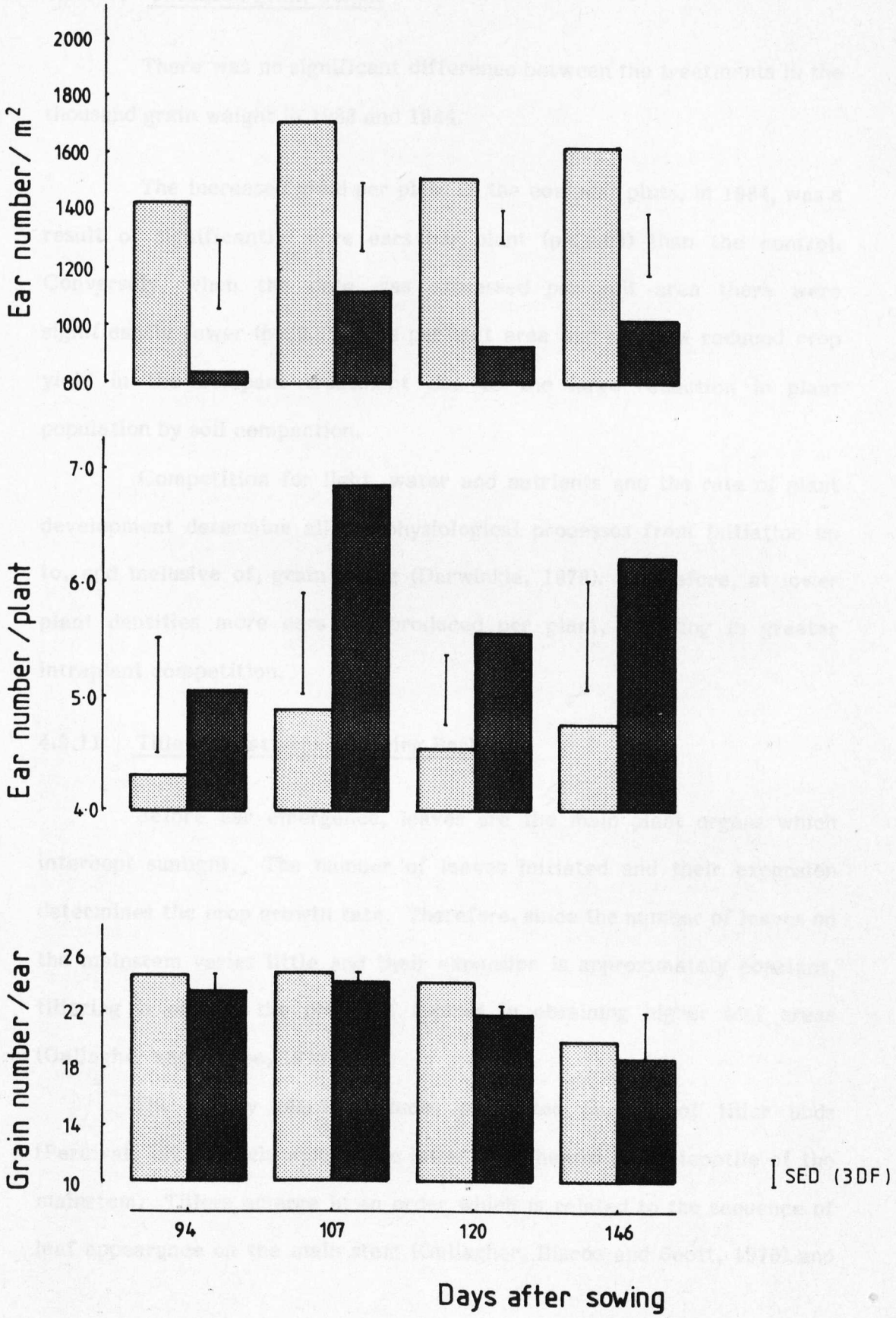
There was no significant difference between the treatments in the number of grains per ear in 1983 or 1984. The decline in grains per ear with time can be seen for both treatments in Figure 4.22.

Table 4.5 Yield components of spring barley

	Control	Compact	DIHB	SED	Sig* (6 DF)
1983					
Ears m^{-2}	1090.0	1016.0	993.0	110.0	NS
Ears $plant^{-1}$	2.98	3.26	2.88	0.26	NS
Grains ear^{-1}	19.7	20.1	21.9	0.45	NS
Thousand grain weight (g)	32.8	84.3	32.5	2.4	NS
Plants m^{-2}	365.0	313.0	344.0	24.9	NS
1984					(3 DF)
Ears m^{-2}	1656.0	1054.0	-	248.0	$p<0.05$
Ears $plant^{-1}$	4.75	6.20	-	0.95	$p<0.05$
Grains ear^{-1}	19.8	18.6	-	2.5	NS
Thousand grain weight (g)	30.4	32.1	-	4.0	NS
Plants m^{-2}	344.0	171.0	-	21.0	$p<0.01$

* level of statistical significance

Figure 4.22 The effect of soil compaction on the number of ears per unit area, ears per plant and grains per ear of spring barley in 1984. Control ▒; Compact ■


Ear number / m²
2000
1800
1600
1400
1200
1000
800
Ear number /plant
7·0
6·0
5·0
4·0
Grain number /ear
26
22
18
14
10
SED (3DF)
94
107
120
146
Days after sowing

4.3.10.4 Thousand grain weight

There was no significant difference between the treatments in the thousand grain weight in 1983 and 1984.

The increased yield per plant in the compact plots, in 1984, was a result of significantly more ears per plant ($p<0.05$) than the control. Conversely, when the data was expressed per unit area there were significantly fewer ($p<0.05$) ears per unit area and hence a reduced crop yield in the compact treatment due to the large reduction in plant population by soil compaction.

Competition for light, water and nutrients and the rate of plant development determine all the physiological processes from initiation up to, and inclusive of, grain filling (Darwinkle, 1978). Therefore, at lower plant densities more ears are produced per plant, resulting in greater intraplant competition.

4.3.11 Tillering Patterns of Spring Barley

Before ear emergence, leaves are the main plant organs which intercept sunlight. The number of leaves initiated and their expansion determines the crop growth rate. Therefore, since the number of leaves on the mainstem varies little and their expansion is approximately constant, tillering is one of the principal factors in obtaining higher leaf areas (Gallagher and Biscoe, 1978).

The barley plant produces a limited number of tiller buds (Percival, 1921) which arise in the lower leaf sheaths and coleoptile of the mainstem. Tillers emerge in an order which is related to the sequence of leaf appearance on the main stem (Gallagher, Biscoe and Scott, 1976) and

the total number of tillers produced per plant decreases with increasing plant density.

As a result of the established effects of soil compaction on plant population (Hebblethwaite and McGowan, 1980; Dawkins, 1982) it was considered to be most important to investigate whether the tillering pattern of spring barley offered some compensation for the low plant numbers which are frequently found in compact soil.

The change in the number of tillers of spring barley with time in 1983 is shown in Figure 4.23. Initially, there were significantly more ($p<0.05$) tillers produced by the control plants as the season progressed but competition for light, water and nutrients possibly resulted in the death of more tillers from the control than from the compact treatment, so that there was no difference between the treatments in the final number of tillers.

In 1984, a tiller-ringing procedure was used to establish whether compaction had any effect on the production and survival of tillers.

The pattern of tillering in 1984 is shown in Figure 4.24. In mid-May (38 days after sowing), significantly more ($p<0.001$) tillers were found on plants from the control treatment although by the time maximum tillering was achieved (59 days after sowing), there was no difference between the treatments. Tiller death was greatest in the control treatment which had lost 16% of the maximum number of tillers produced by harvest, whereas only 9% of the tillers had died in the compact treatment.

Tillering is a flexible response which enables the plant to compensate for a wide range of densities, resulting from poor or variable establishment and adverse environmental conditions (Kirby and Faris,

Figure 4.23 The influence of soil compaction on the number of tillers of spring barley in 1983. Control o ; Compact ●

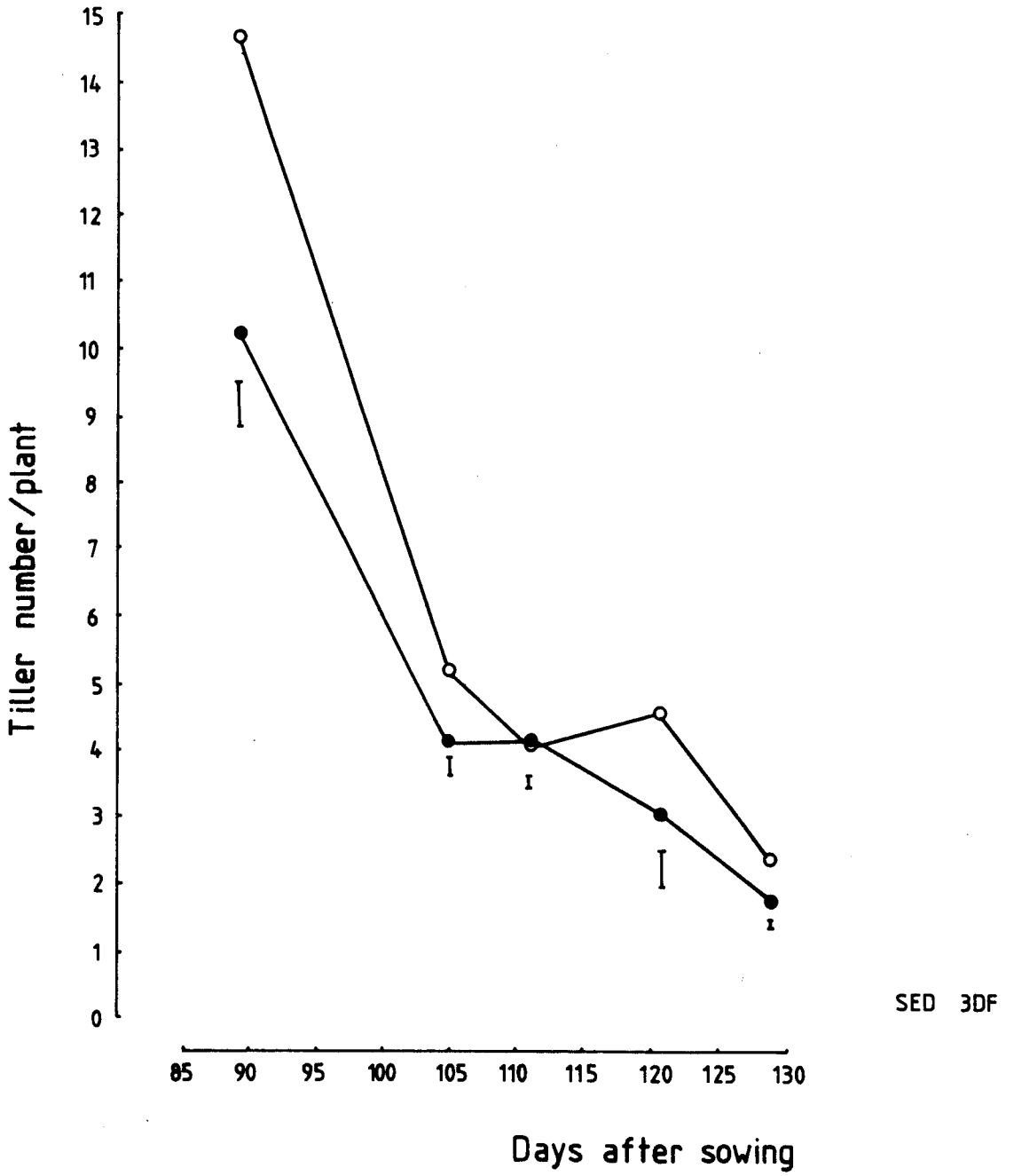
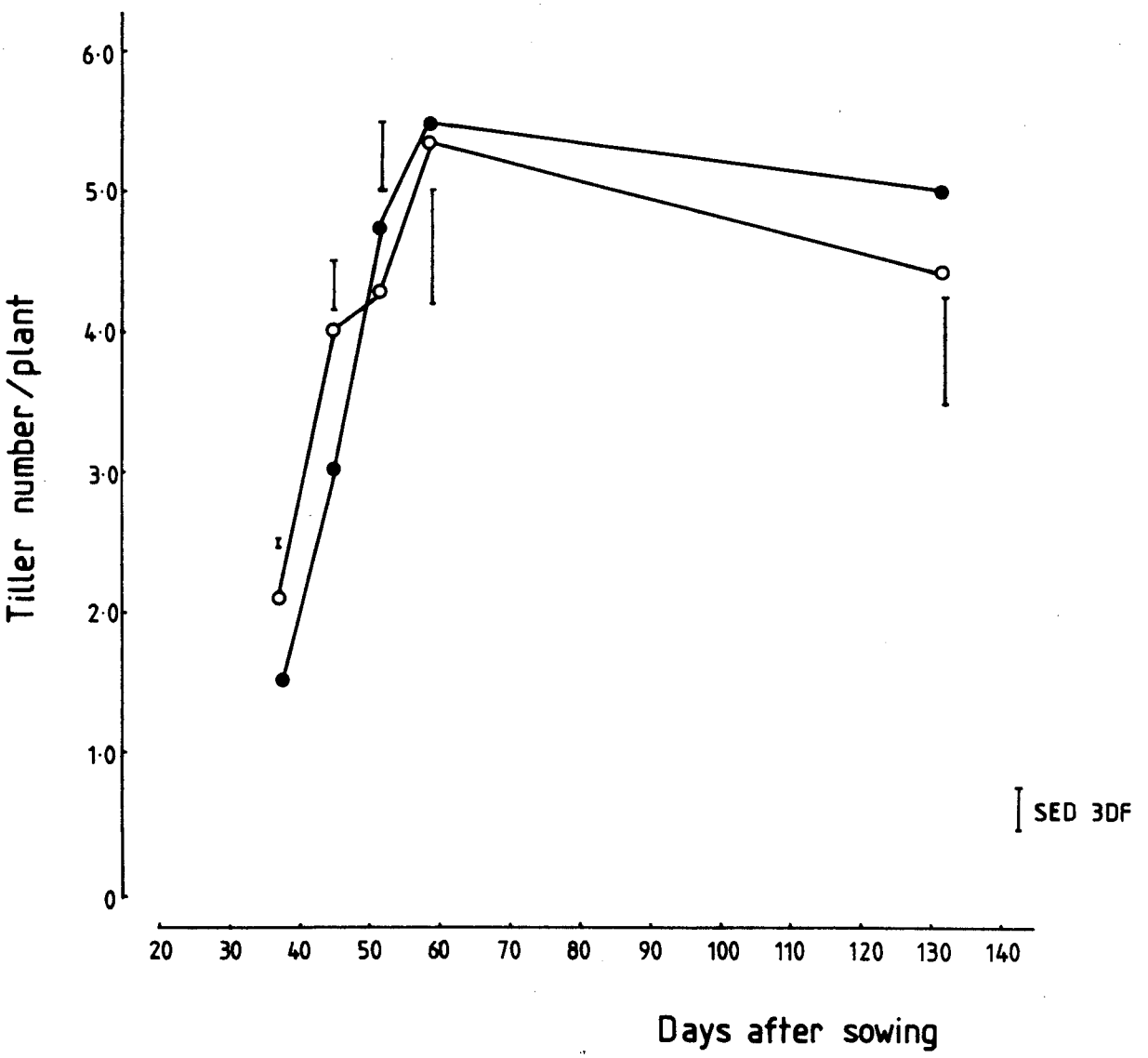

Tiller number/plant
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
85
90
95
100
105
110
115
120
125
130
Days after sowing
SED 3DF

Figure 4.24 The influence of soil compaction on the number of tillers of spring barley in 1984. Control o ; Compact ●


Tiller number/plant
6·0
5·0
4·0
3·0
2·0
1·0
0
20
30
40
50
60
70
80
90
100
110
120
130
140
Days after sowing
SED 3DF

1970). This probably accounts for the wide range of near-optimum seed rates found in barley.

The effect of plant population on tillering has been well documented (Aspinall, 1961; Thorne, 1962; Darwinkle, 1978). Puckeridge and Donald (1967) reported that the survival of tillers (tiller efficiency) was found to decrease with increasing plant density. It is therefore possible that a greater interplant and intraplant competition existed in the control treatment with a larger plant population than in the compact treatment and that this greatly affected tiller death which is known to be dependent on light, water and nutrient supply (Thorne, 1962).

Figure 4.25 shows the number of tillers produced by plants of the compact and control treatments between successive sampling dates and also the amount of these tillers which survived until harvest.

The compact crop produced fewer tillers than the control between each sampling date except between 45 and 52 days after sowing when significantly more tillers ($p<0.01$) were produced in the compacted treatment. Therefore as a consequence of a greater tiller production between 45 and 52 days after sowing and a greater retention of existing tillers, the compact crop possessed more tillers, and hence more ears, per plant at harvest. The result was a larger individual grain yield per plant than in the control.

The contribution of the tillers produced between the successive sampling dates to the grain yield per plant is shown in Table 4.6. The greater number of tillers produced by the control crop ($p<0.001$) before 38 days after sowing contributed to a significantly higher ($p<0.05$) grain weight per plant than in the compact treatment. However the increased tillering of the compact plants between 45 and 52 days after sowing

Figure 4.25 The influence of soil compaction on the number of tillers produced between successive sampling dates and on the numbers of these tillers which survived until harvest

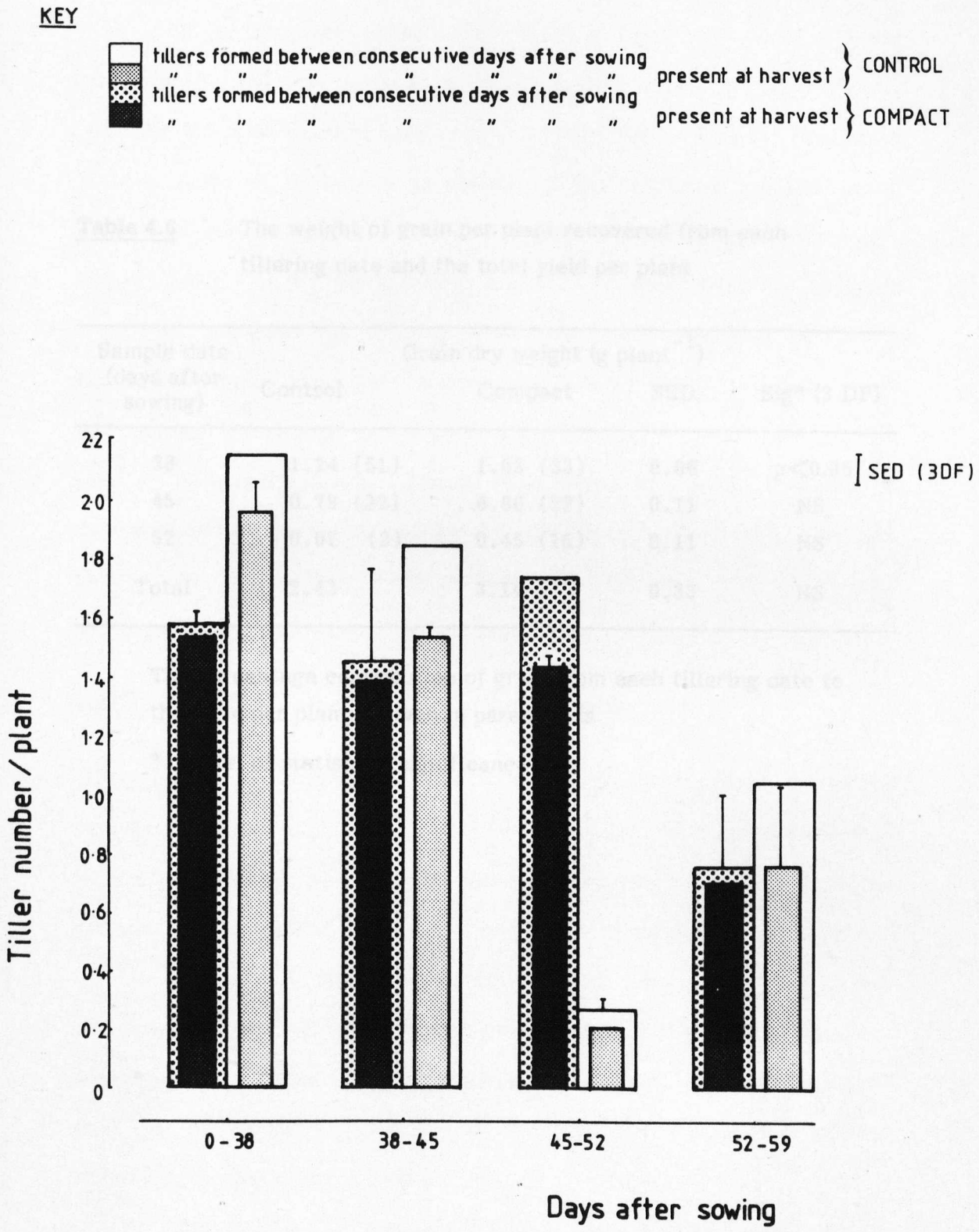

KEY
tillers formed between consecutive days after sowing
" " " " " " "
present at harvest
CONTROL
tillers formed between consecutive days after sowing
" " " " " " "
present at harvest
COMPACT
SED (3DF)
Tiller number / plant
2·2
2·0
1·8
1·6
1·4
1·2
1·0
0·8
0·6
0·4
0·2
0
0 - 38
38 - 45
45 - 52
52 - 59
Days after sowing

Table 4.6 The weight of grain per plant recovered from each tillering date and the total yield per plant

Sample date (days after sowing)	Grain dry weight (g plant^{-1}) Control	Compact	SED	Sig* (3 DF)
38	1.24 (51)	1.03 (33)	0.06	$p<0.05$
45	0.79 (32)	0.86 (27)	0.11	NS
52	0.07 (3)	0.45 (15)	0.11	NS
Total	2.43	3.14	0.33	NS

The percentage contribution of grain from each tillering date to the yield per plant is given in parenthesis

* level of statistical significance

resulted in a significantly greater ($p<0.001$) grain weight per plant than the control and consequently a larger total grain yield per plant (NS).

It is therefore evident that tillering forms the basis of yield compensation and thus enables the crop to further exploit its environment. However the production of tillers which do not contribute to the final grain yield is wasteful, because a proportion of the resources are lost which cannot be retranslocated to surviving parts of the plant (Rawson and Donald, 1969). At plant densities as low as those observed in the compact treatment, and increased tillering, in spite of an accompanying increase in ear weight from 3.33 g plant^{-1} (control) to 4.23 g plant^{-1} (compact), could not maintain the yield up to the level of the control.

Although individual plants were found to exhibit a degree of compensation, it was not possible to exclude the direct effect of soil compaction on individual plant performance because a 'control thinned' treatment was not employed in the 1984 trial.

4.3.12 Delayed Senescence and Grain Ripening in 1984

In order to study the delay in grain ripening observed in the compact treatment, a unit area of each treatment was hand-harvested at 14 and 7 days before final harvest. Samples were taken to a static thresher and the grain was collected, weighed and the moisture content determined.

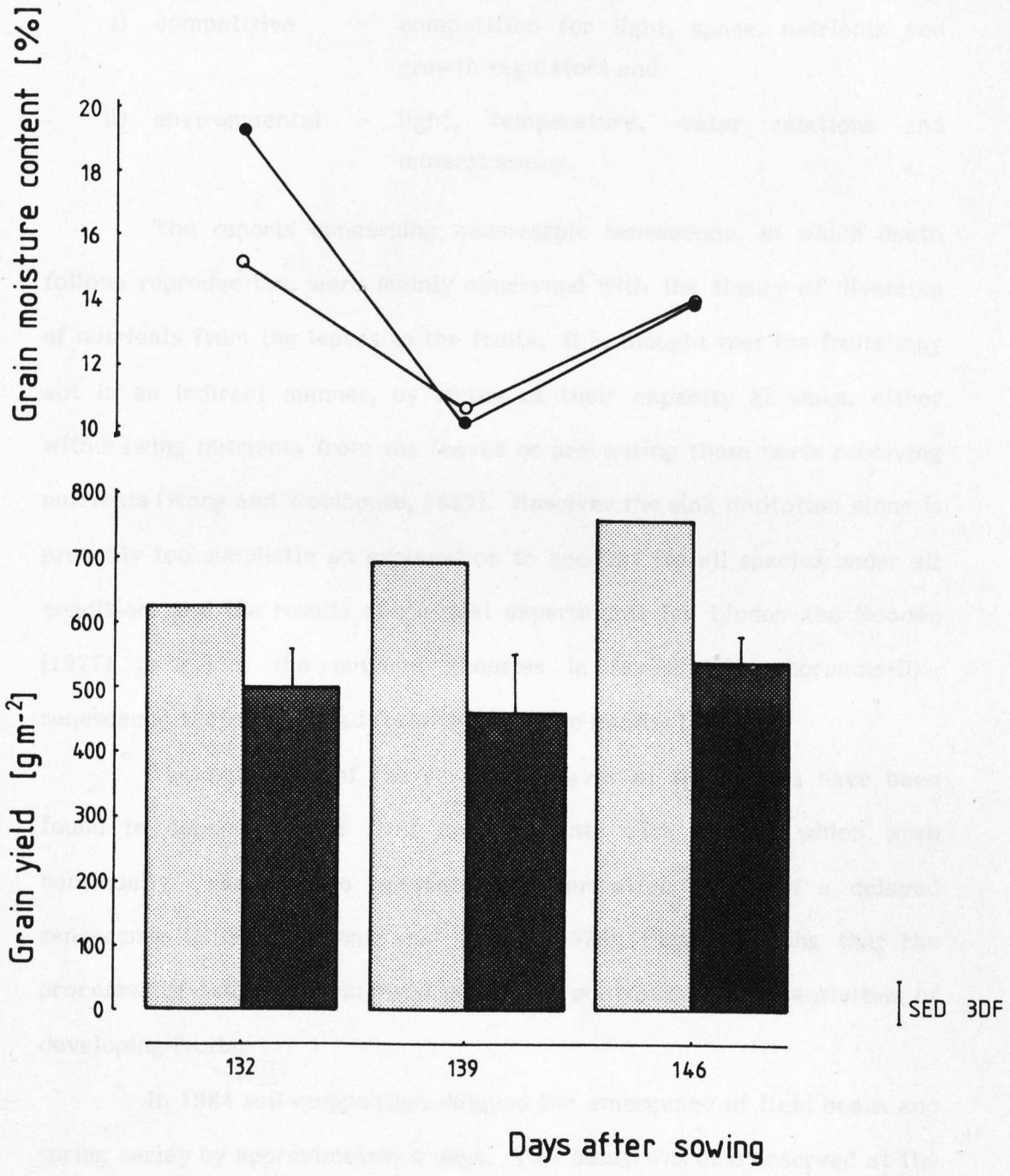
At each harvest, the control yielded more than the compact treatment (Figure 4.26) by virtue of its higher population. The moisture content of the compact treatment sample was significantly higher ($p<0.01$) than that of the control at the first sampling at 132 days after sowing, which suggested a delay in crop maturity.

Soil compaction was also found to delay the leaf senescence of spring barley in 1983 and 1984 and of field beans in 1984.

Figure 4.26 The influence of soil compaction on the yield of spring barley per unit area and the grain moisture content at 14 and 7 days before final harvest.

Grain moisture: Control (o); Compact (●)

Grain yield: Control ▒; Compact ■


Grain moisture content [%]
20
18
16
14
12
10
Grain yield [g m-2]
800
700
600
500
400
300
200
100
0
SED 3DF
132
139
146
Days after sowing

Thomas and Stoddart (1980) reviewed the extensive literature on leaf senescence. They found that the external factors which influenced the initiation of senescence were principally:

i) competitive - competition for light, space, nutrients and growth regulators and

ii) environmental - light, temperature, water relations and mineral status.

The reports concerning monocarpic senescence, in which death follows reproduction, were mainly concerned with the theory of diversion of nutrients from the leaves to the fruits. It is thought that the fruits may act in an indirect manner, by virtue of their capacity as sinks, either withdrawing nutrients from the leaves or preventing those parts receiving nutrients (Wang and Woolhouse, 1982). However the sink limitation alone is probably too simplistic an explanation to account for all species under all conditions and the results of surgical experiments led Lindoo and Noodén (1977) to reject the nutrient theories in favour of a hormone-like senescence factor exported from the fruits to nearby leaves.

The activities of the surviving leaves of field beans have been found to depend on the fruit load. Plants with flowers which were continually removed to prevent fruit formation exhibited a delayed senescence (Hill-Cottingham and Turner, 1976), thus indicating that the processes of senescence in field beans are controlled by the activities of developing fruits.

In 1984 soil compaction delayed the emergence of field beans and spring barley by approximately 4 days. This delay was also observed at the time of stem extension and at anthesis in field beans when the compact crop commenced flowering approximately 4 days after the control. It is

therefore possible that the delayed senescence at the end of the season was a direct consequence of the delayed emergence at the beginning of the season. Further work is required to study the influence of soil compaction on crop senescence in order to achieve a more complete understanding of how soil compaction affects crop growth and development.

Chapter 5

LEAF EXPANSION, LIGHT INTERCEPTION AND CONVERSION EFFICIENCY

5.1 Introduction

In the early part of the growing season, the rate of dry matter accumulated by arable crops is proportional to the amount of radiation intercepted by the foliage (Shibles and Weber, 1965; Monteith, 1977; Gallagher and Biscoe, 1978) and in turn the crop yield is related to the cumulative radiation interception (Sibma, 1970; Duncan, Shaver and Williams, 1973; Scott, English, Wood and Unsworth, 1973; Green, 1984a).

The development of sufficient leaf canopy to intercept an extensive proportion of the incident solar radiation is perhaps the most important factor responsible for determining the yield of any arable crop. If crops are subjected to stresses which restrict the area of leaf available to intercept the radiation or which reduce the efficiency with which this radiation is converted to dry matter, the crop yield will inevitably be reduced.

This chapter investigates the effect of soil compaction on the development of the leaf canopy; the degree of light interception and the conversion efficiency of field bean, spring barley and sugar beet.

5.2 Materials and Methods

5.2.1 Planimetric Determination of Canopy Area

The plant samples which were collected for destructive growth analysis (Sub-section 4.2) were taken from the cold storage room and any

fibrous root matter was removed. The leaf laminae were removed from a known sub-sample of plants and the areas were measured using a moving belt electronic planimeter (Li. Cor. Inc., Model 3100). The instrument was recalibrated with a 50 cm^2 metal disc before and after use, to ensure accurate readings. The belts were cleaned regularly with moist tissue paper.

5.2.2 Leaf Lamina Expansion

5.2.2.1 Sequential leaf expansion

In situ measurements of lamina expansion were made on field beans and sugar beet crops in 1984. Ten representative plants from each plot were ringed and numbered. The length and widest breadth of individual leaves or leaflets was measured weekly with a rule until maximum size was attained. The lamina area was considered to be the product of the length, breadth and a calibration factor. This was calculated from the relationship between the 'planimetric' lamina and the 'rule' lamina areas, as measured in the laboratory. The number of the leaf measured was similar for all plants and each treatment. Leaf (1) was taken to be the first leaf or leaflet from ground level and the number ascended up the plant.

5.2.2.2 Single leaf expansion

Ten field bean and sugar beet plants were selected and ringed. The length and breadth of the last leaf to appear, irrespective of its 'morphological' number, was measured at two-day intervals until the full size was achieved. These measurements were then converted into area, using the technique described above.

5.2.3 Photographic Determination of Canopy Development

Measurements of foliage cover were obtained from vertical photographs, taken with a 35 mm camera and a standard 50 mm lens at a height of 2 m above the crop. The maximum field of view was $\pm$ 23° from the vertical. The height of the camera above the crop was not critical provided that several rows of crop could be photographed and a sufficient depth of field could be achieved so that all the canopy was in focus (Stevens, Biscoe, Jaggard and Paruntu, 1985). Photographs were taken weekly in 1984, until the percentage ground cover was constant.

The photographs were analysed manually by projecting the transparency onto a randomised grid and by counting the number of points falling upon the leaves or upon the soil. The fractional foliage cover was considered to be the proportion of points falling upon the green crop canopy. A randomised grid was used in preference to a line grid to prevent the possibility of an interaction between the line grid spacing and the row spacing of the crop. The method of construction of a randomised grid and the associated errors have been described by Stevens et al. (1985).

5.2.4 Tube Solarimeter Determination of Canopy Development

The interception of the total incoming shortwave radiation (300-2000 nm) by a crop, was measured by using a tube solarimeter (Szeicz, Monteith and Dos Santos, 1964) consisting of a series of copper/constantan thermocouple junctions, connected to produce a thermopile (Monteith, 1959; Steven, 1977). This method has the advantage of providing spatial averaging at low cost.

5.2.4.1 Method of solarimeter operation

The standard procedure for the construction of a thermopile was described by Moneteith (1959), Szeicz et al. (1964) and Steven (1977). An increase in solar intensity leads to an increase in the temperature difference between the black-painted 'hot' junctions and the white-painted 'cold' junctions (Monteith, 1959). The temperature difference between the junctions produces a current proportional to the intensity of light incident on the thermopile (Steven, 1977).

5.2.4.2 Solarimeter construction

Lancashire (1981) improved the construction of the thermopile tube solarimeter by using an etched printed circuit board to form copper strips which were joined by constantan wire. The full procedure for the construction of the solarimeter used in the field trial was described by Green (1984a).

5.2.4.3 Solarimeter installation

The incident radiation was measured by two solarimeters, placed 0.3 m above fallow ground and clipped into telescopic stands. The solarimeters were orientated in an east-west direction to produce optimum radiation distribution (Szeicz et al., 1964). A spirit level was used to ensure horizontal installation. The solarimeters were placed in four replicates of each treatment, across the rows, just after sowing. This enabled the crop to grow around them and thus prevented a large displacement of the canopy on installation. However, the glass required frequent cleaning and part of the crop was necessarily disturbed, which

resulted in a slight underestimation of the light intercepted by both treatments.

Green (1984a) investigated the effect of solarimeter position, relative to the plot edge, on light transmission. He calculated that if the centre of a solarimeter was placed any nearer than 1.2 m from the plot edge (at 90° to that edge) then the transmission would be overestimated. However, the trial plots were 2.5 m wide and therefore the ends of a 1.0 m tube solarimeter would not be less than 0.75 m from the plot edge. Green (1984a) reported that solarimeters used in plots of 2.5 m width would measure a representative level of light transmission.

5.2.4.4 Integration

Measurements of light interception made from instantaneous readings of light intensity are subject to large variation due to the influence of the wind on cloud and canopy motion. Therefore, the solarimeter output was integrated over time using a millivolt integrator of the Campbell (1974) design, as modified by Saffel, Campbell and Campbell (1979).

Solar radiation was integrated at identical intervals on (4-5 hrs) either side of noon (GMT). This helped to standardise the effects of the sun angle between the days and ensured that the light was measured when crossing the solarimeters at similar angles on each side (Green, 1984a).

5.2.4.5 Measurement of daily irradiance

The daily incident solar radiation was measured at Sutton Bonington Meteorological Station using a Kipp pyranometer connected to a millivolt integrator. When measurements were not available due to

instrument failure, the irradiance was estimated from the number of sunshine hours, by the following relationship:

$$S_t = S_o (a + b\, n/_N)$$

where S_t = total incident solar radiation

S_o = irradiance in the absence of atmosphere

N = the number of hours between sunrise and sunset

a and b are constants (for Sutton Bonington a = 0.15, b = 0.66)

This equation was considered to be accurate to $\pm$ 5% for periods of one week or more but errors were greater if the relationship was used for shorter periods (Gallagher and Biscoe, 1978).

5.2.4.6 Solarimeter calibration

The tube solarimeters were calibrated, in direct and diffused light, by plotting the measured output against the measured shortwave radiation (Kipp pyranometer). The slope of this relationship provided a calibration constant for each solarimeter.

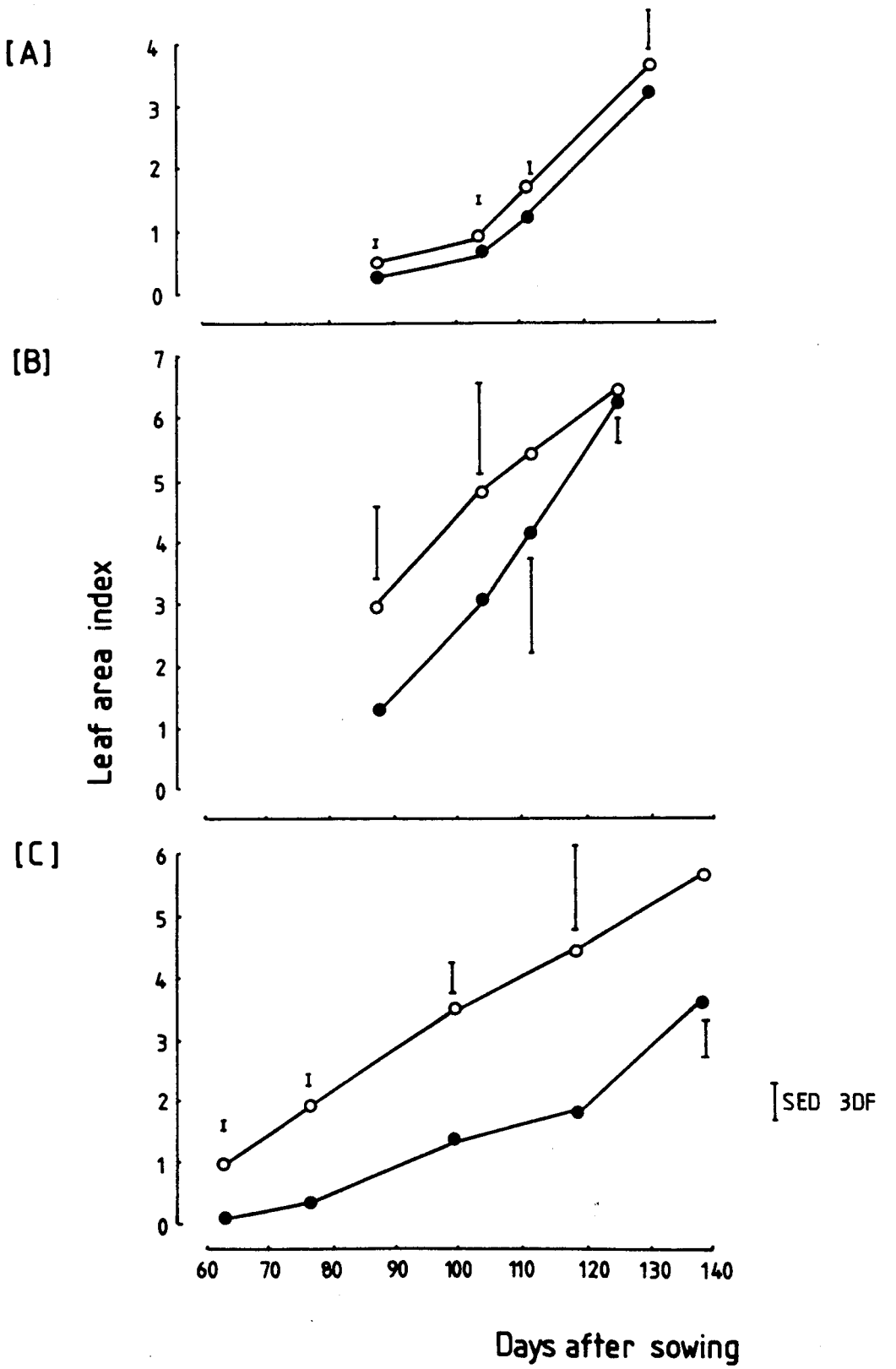
5.3 Results and Discussion

5.3.1 Leaf Area

The Leaf Area Index (LAI) is the ratio of green leaf area (m^2) to ground area (m^2).

In 1983, the LAI of field beans, spring barley and sugar beet was lower in the compact treatment than in the control (Figure 5.1), however this difference was not significant in the spring barley crop. Biscoe and Gallagher (1977) reported that for most crops a LAI of between 4 and 5 was

Figure 5.1 The effect of soil compaction on the Leaf Area Index (LAI) of field bean (A), spring barley (B) and sugar beet (C) in 1983. Control (o); Compact (●)


[A]
[B]
[C]
Leaf area index
0
1
2
3
4
5
6
7
60
70
80
90
100
110
120
130
140
Days after sowing
SED 3DF

required to intercept more than 80% of incident PAR. They suggested that factors which limited the rate of the expansion of the leaf surface would directly limit the dry matter production of the crop until a LAI of 4 to 5 (the 'critical LAI') was achieved. The critical LAI was not achieved in either treatment of field beans in 1983, probably owing to poor establishment of the crop. Spring barley achieved a critical LAI at approximately 100 days after sowing but this was delayed by approximately 12 days in the compact treatment. The sugar beet crop attained a critical LAI of 4.0, (Sugar Beet Research and Education Committee, 1982b) 110 days after sowing, but this was never achieved in 1983 by the compact treatment. It is therefore probable that the productivity of the field bean crop and the sugar beet compact treatment were limited by insufficient leaf cover to exploit the incident radiation.

The leaf area per plant (Figure 5.2) was reduced also in the compact treatment of each crop. The reversal of this trend in spring barley at the end of the monitoring period would suggest that compaction delayed the senescence of the foliage.

In 1983 soil compaction reduced the ability of the sugar beet plant to develop a full leaf canopy and it prevented any compensatory growth of the leaf canopy in response to the low plant population.

In 1984, the LAI of each crop was reduced throughout the season in the compact plots (Figure 5.3). This trend was reversed in field beans at the end of the season indicating that the senescence of the leaf canopy had been delayed in the compact treatment.

The large reduction in plant density found in the compact treatment of each crop was mainly responsible for the reduced production of the leaf area during the establishment phase. However, the data suggest

Figure 5.2 The effect of soil compaction on the leaf area per plant of field bean (A), spring barley (B) and sugar beet (C) in 1983. Control (o); Compact (●)

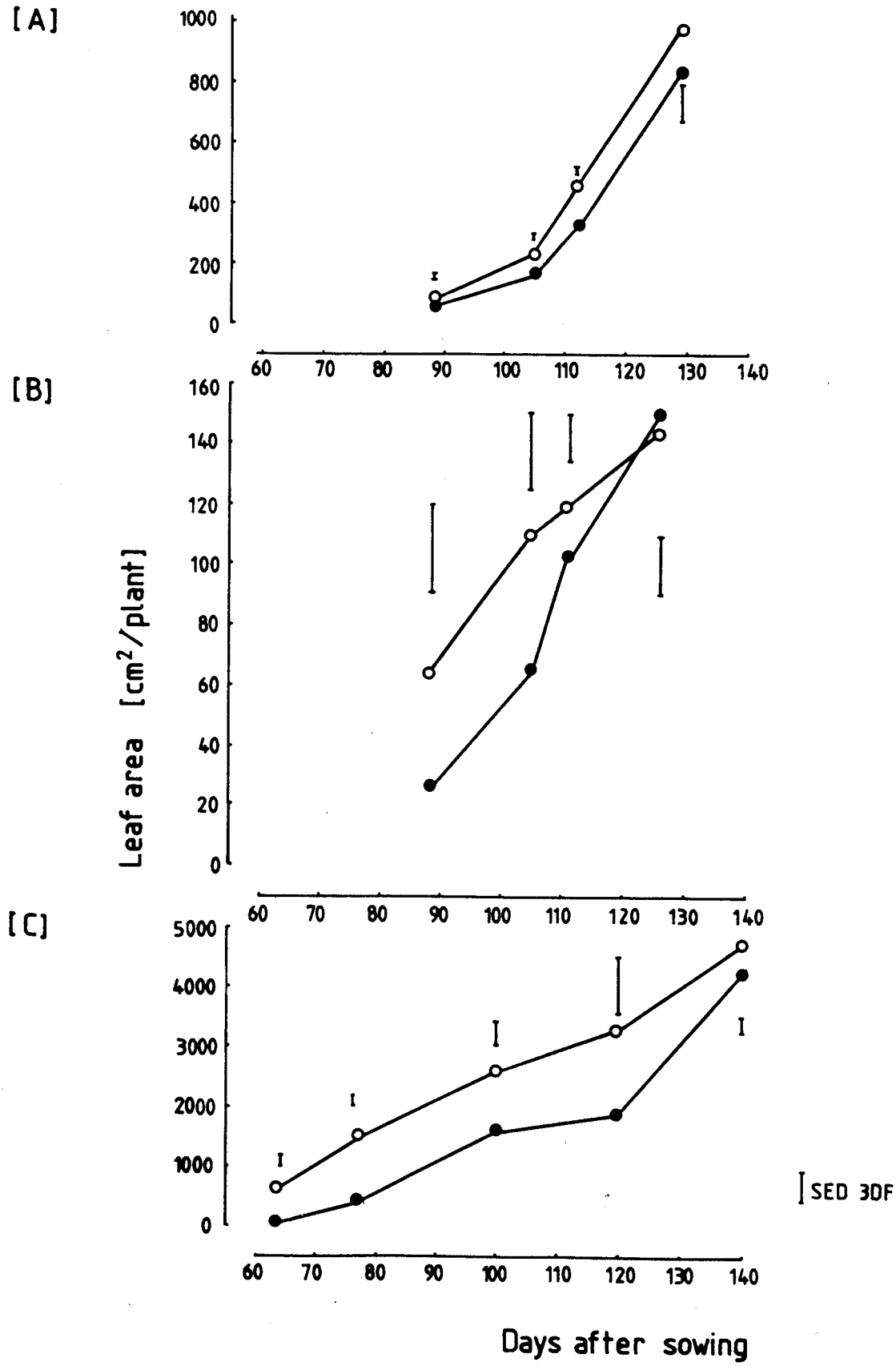
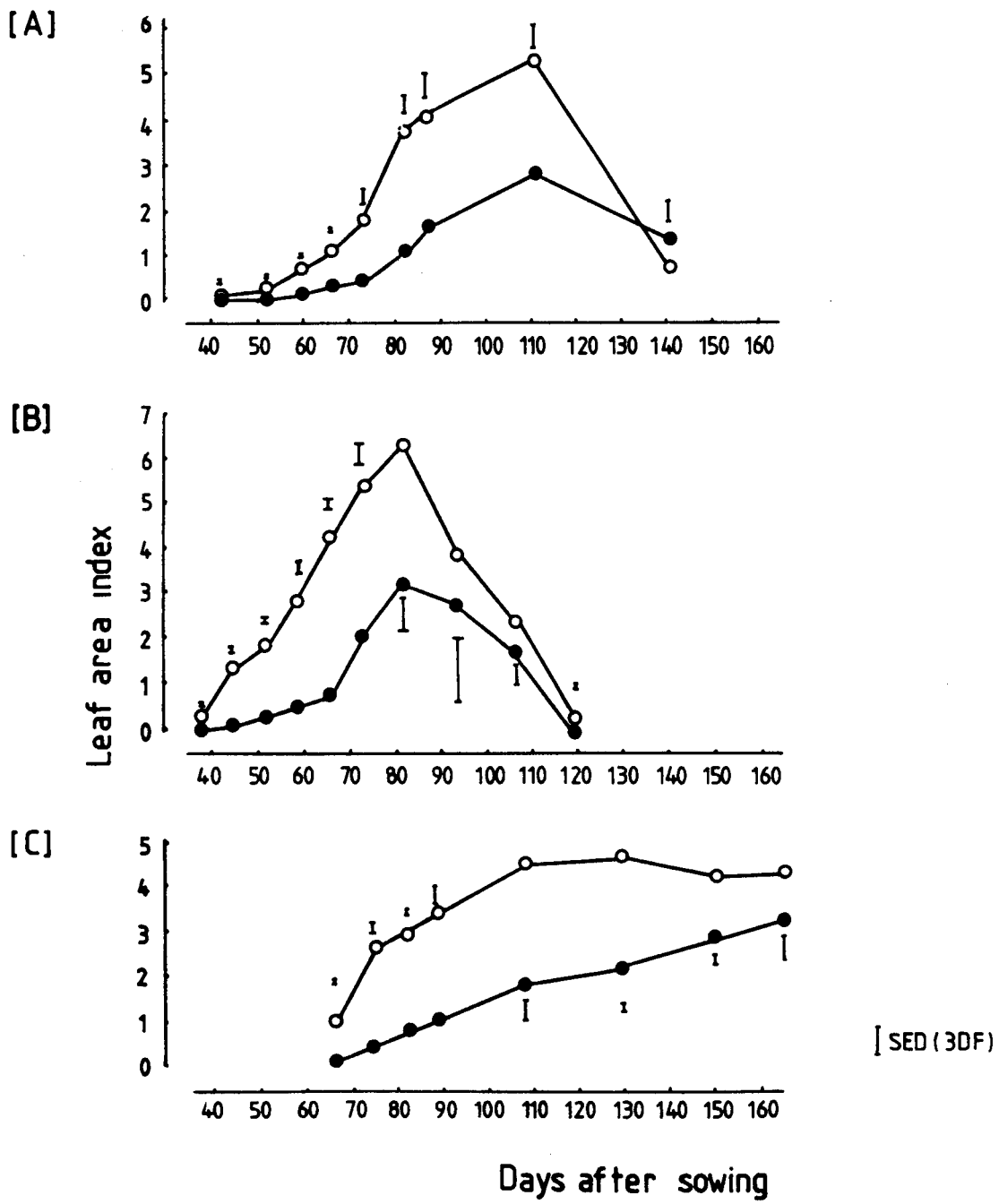

[A]
[B]
[C]
Leaf area [cm²/plant]
Days after sowing
SED 3DF

Figure 5.3 The effect of soil compaction on the Leaf Area Index (LAI) of field bean (A), spring barley (B) and sugar beet (C) in 1984. Control (o); Compact (●)


[A]
[B]
[C]
Leaf area index
Days after sowing
SED (3DF)

(Sub-section 5.3.2) that the individual leaf size was also reduced in the compact treatments.

The beginning of the linear growth phase of field beans and spring barley was delayed, as a result of compaction, by approximately 7 days (Figure 4.4). The reduced maximum LAI of the compact treatment was possibly the result of a lower LAI at the end of the establishment phase and a slower rate of canopy expansion during the linear phase of growth, than with the control crop. The critical LAI was not attained in the compact treatment. The beginning of canopy senescence occurred at approximately 24 days after anthesis of both treatments and this reflects the indeterminant character of this crop to continue concurrent vegetative and reproductive growth.

In spring barley, the consistent reduction in the LAI of the compact treatment during the linear growth phase was probably due to the difference between the treatments in the LAI at the end of canopy establishment, since both treatments showed a similar rate of canopy expansion during the linear phase. Anthesis, which terminated the production of leaf area was not delayed by compaction. The critical LAI was achieved between 65 and 70 days after sowing. However the compact spring barley treatment never achieved the critical LAI, reaching a maximum value of only 3.3 which severely limited the productivity of this treatment.

The LAI of the control sugar beet treatment increased linearly with time until 108 days after sowing when it then plateaued and achieved a maximum value of 4.7, at approximately 22 days later. The LAI of the compact treatment increased steadily throughout the season to a maximum value of 3.3 at harvest time. The critical LAI was achieved by the control

treatment, at 100 days after sowing, when the compact treatment had only 38% of the required leaf cover to intercept 80% of the incident radiation. The pattern of the sugar beet crop growth changes on attainment of the critical LAI. This stage is associated with the 'maturing' of the crop when older leaves are generally replaced by younger leaves, thus enabling the assimilate to be used for dry matter accumulation in the tap root.

Although the difference in LAI between the treatments was not significant at harvest, the yield of sugar beet was reduced significantly by compaction (Chapter 4), since the yield was closely correlated with the quantity of radiation intercepted by the canopy throughout the season (Scott et al., 1973).

The Leaf Area Duration (LAD), here defined as the LAI integrated with respect to time, was calculated in 1984 from the area beneath the curve. Soil compaction reduced the expansion phase of the canopy in all crops (Table 5.1). The difference between the treatments was largely a result of the reduced LAI of the compact treatments, since differences in the persistence of the green canopy were not measured. The reduction in the LAD of the senescent phase by compaction was not found to be significant.

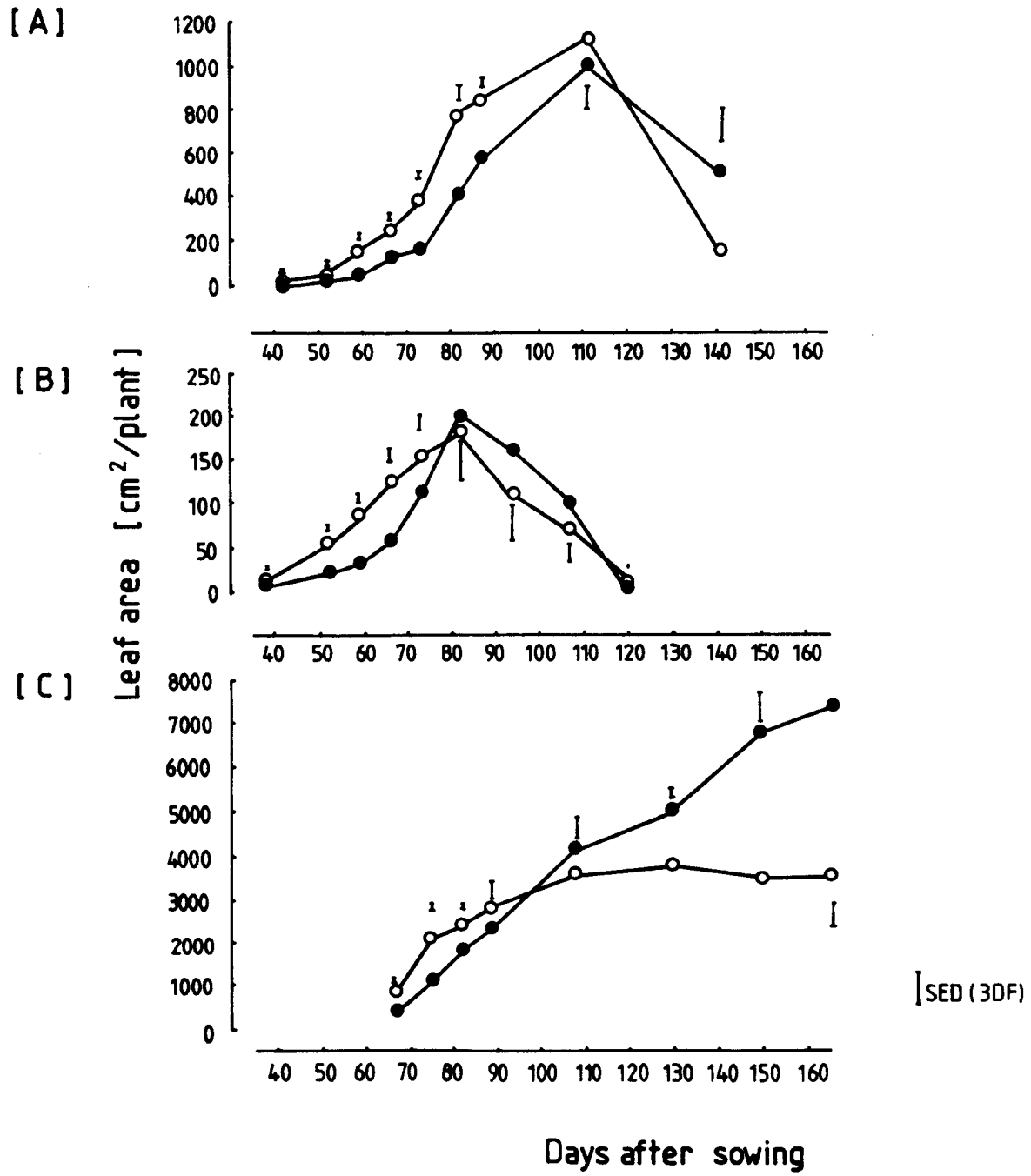
The leaf area per plant was initially reduced by soil compaction in each crop (Figure 5.4). However, in contrast to the 1983 trial, this trend was reversed during the 1984 season, partly because of compensatory growth resulting from the reduced plant population of the compact treatment and partly because of a delayed senescence in the compact plots of field beans and spring barley.

Table 5.1 The effect of compaction on the Leaf Area Duration (LAD) of field beans, spring barley and sugar beet in 1984

	LEAF AREA DURATION (days)			
	Control	Compact	SED	Sig* (3 DF)
FIELD BEANS				
Expansion phase	88.0	38.0	10.0	$p<0.01$
Senescence phase	43.0	30.0	6.5	NS
SPRING BARLEY				
Expansion phase	79.0	22.0	13.0	$p<0.01$
Senescence phase	54.0	44.0	9.5	NS
SUGAR BEET				
Expansion phase	198.0	94.0	14.5	$p<0.01$
Senescence phase	-	-	-	-

* level of statistical significance

Figure 5.4 The effect of soil compaction on the leaf area per plant of field bean (A), spring barley (B) and sugar beet (C) in 1984. Control (o); Compact (●)


[A]
[B]
[C]
Leaf area [cm²/plant]
1200
1000
800
600
400
200
0
250
200
150
100
50
8000
7000
6000
5000
4000
3000
2000
1000
40 50 60 70 80 90 100 110 120 130 140 150 160
SED (3DF)
Days after sowing

5.3.2 Leaf Expansion

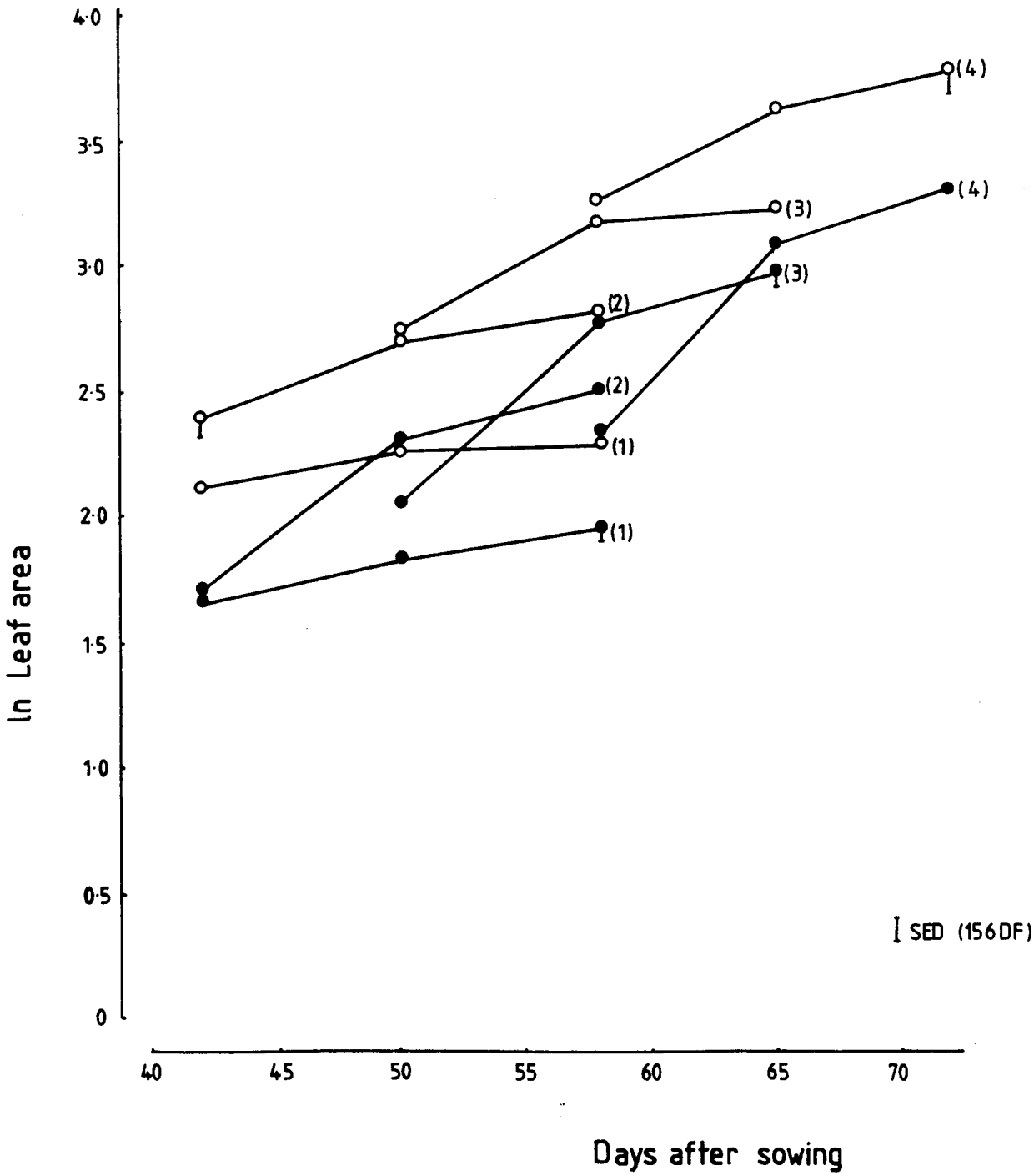
The LAI is related to the number and the size of the individual leaves and the way in which they are retained on the plant, while the leaf size is a product of the mean growth rate and the duration of growth (Dennet, Auld and Elston, 1978). Therefore in order to achieve a better understanding of how soil compaction affects the development of the leaf canopy, it was necessary to study the expansion of individual leaves.

5.3.2.1 Sequential leaf expansion

Sequential measurements of lamina expansion were made on individual leaves of field bean (Figure 5.5) and sugar beet plants (Figure 5.6) in 1984. Since the variability of the data increased with an increasing lamina size, the natural logarithm of the area was used in order to equalize the errors throughout the observation period and thus to study the interaction of the lamina area with time.

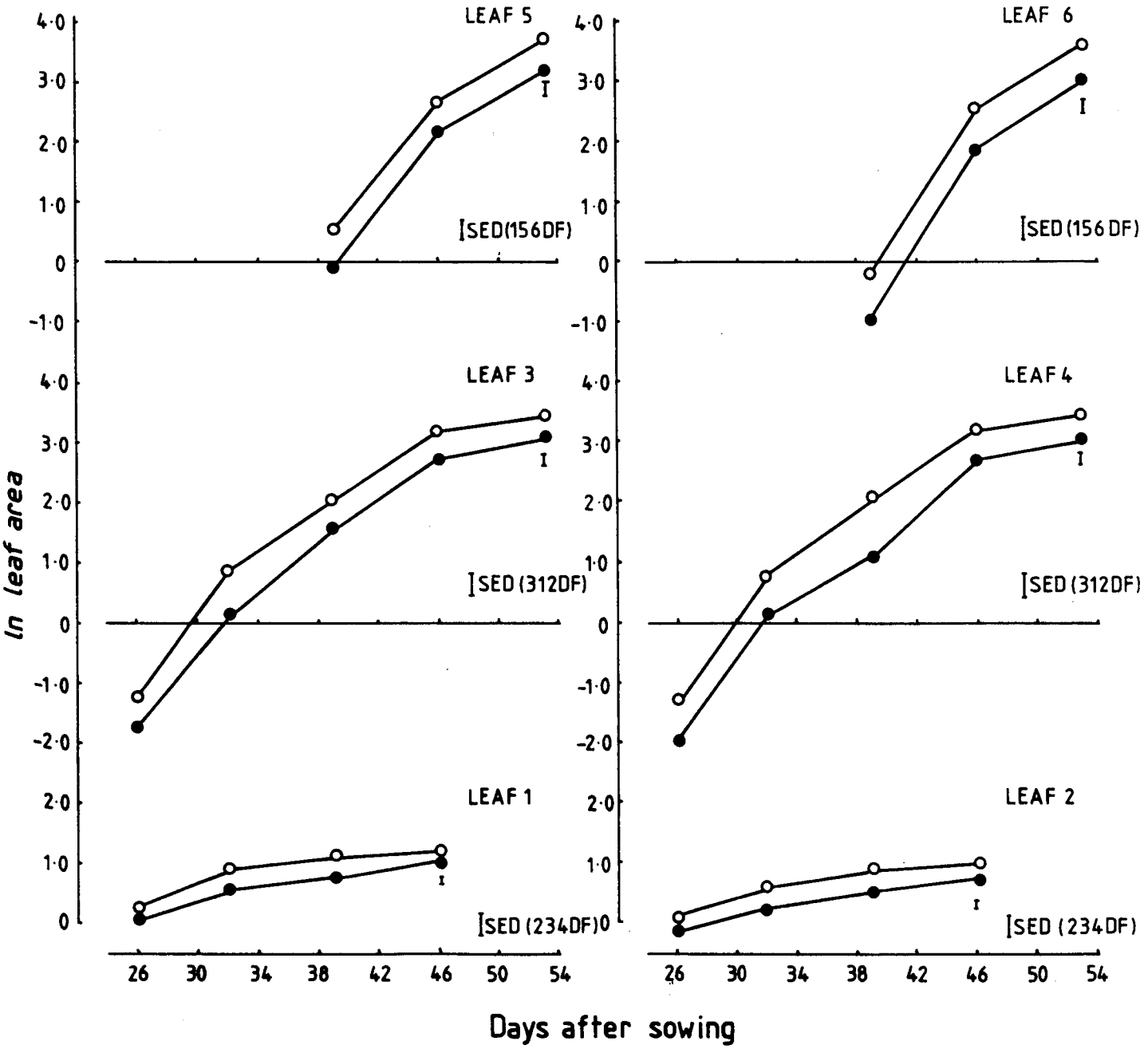
Soil compaction reduced significantly ($p<0.01$) the lamina area of field beans at each date for every leaf measured. The difference between the treatments diminished over the observation period for leaves 2, 3 and 4. However this was considered to be the result of the reduced expansion rate of the control leaves as they reached maximum size and was not due to an increase in the rate of leaf expansion in the compact treatment. Each leaf studied in the compact treatment was smaller than the control at the beginning of the monitoring period. This would suggest that compaction had either delayed leaf initiation or had delayed the unfolding of the leaf prior to expansion.

Figure 5.5 The influence of soil compaction on the lamina expansion of a number of individual field bean leaves in 1984. Control (o); Compact (●). [leaves of same 'morphological number']


4·0
3·5
3·0
2·5
2·0
1·5
1·0
0·5
0
ln Leaf area
40
45
50
55
60
65
70
Days after sowing
(4)
(3)
(2)
(1)
(4)
(3)
(2)
(1)
I SED (156DF)

( ) LEAF NUMBER

Figure 5.6 The influence of soil compaction on the lamina expansion of a number of individual sugar beet leaves in 1984. Control (o); Compact (●). [leaves of same 'morphological number']


LEAF 5
LEAF 6
LEAF 3
LEAF 4
LEAF 1
LEAF 2
SED(156DF)
SED (312DF)
SED (234DF)
4·0
3·0
2·0
1·0
0
-1·0
-2·0
26
30
34
38
42
46
50
54
ln leaf area
Days after sowing

With sugar beet, there was a trend at each date for the area of every leaf to be reduced in the compact treatment. However the difference between the treatments was significant ($p<0.05$) only for leaves 3, 4 and 5 but there was no difference in the rate of leaf expansion.

All the sugar beet leaves grew in pairs in such a manner that both members of the pair were of a similar size at any point in time. The measurements of leaf number (Figure 5.7), made later in the season on growth analysis samples, showed that compaction delayed initially the appearance of leaves. This trend was reversed, 95 days after sowing, when compensatory growth in the compact treatment resulted in significantly more leaves per plant ($p<0.05$) than in the control.

5.3.2.2 Single leaf expansion

In order to ascertain whether the response of leaf expansion to soil compaction was influenced by the position of the leaf on the plant, measurements of the lamina area of the most recent leaf to appear, irrespective of the number of that leaf, were made in 1984 on field bean (Figure 5.8) and sugar beet plants (Figure 5.9).

There was a trend for the lamina area of both the field bean and the sugar beet leaves to be reduced in the compact treatment and this trend, with a consequent reduction in the maximum leaf size, continued throughout the monitoring period. It was therefore evident that compaction reduced the individual leaf size but not the rate of leaf expansion and that this response was unaffected by the leaf number.

The initiation, unfolding and expansion of leaves is linearly related to temperature (Milford, 1982) and the duration of leaf expansion can be changed by crop husbandry, such as crop nutrition. The Sugar Beet

Figure 5.7 The influence of soil compaction on the production of leaves by sugar beet plants in 1984.
Control (o); Compact (●)

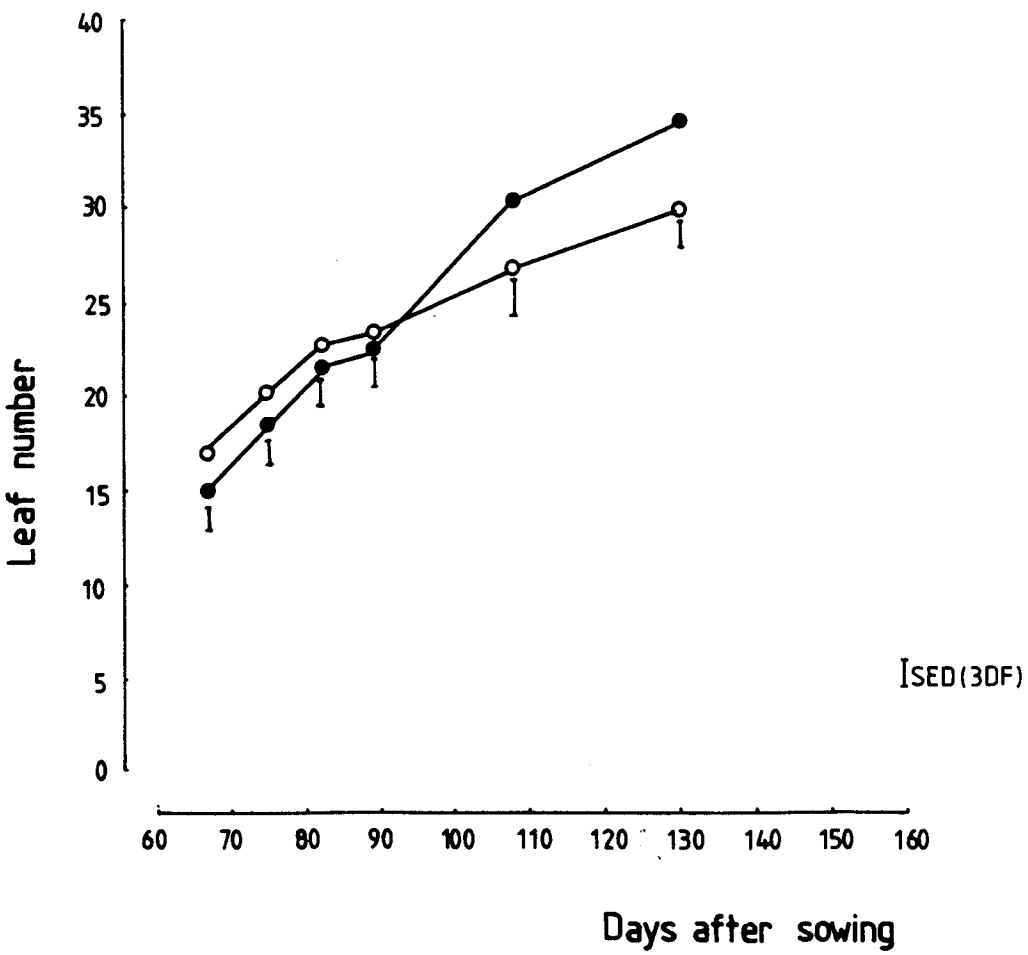

40
35
30
25
20
15
10
5
0
Leaf number
ISED(3DF)
60
70
80
90
100
110
120
130
140
150
160
Days after sowing

Figure 5.8 The influence of soil compaction on the lamina expansion of a single field bean leaf in 1984. [leaves of different 'morphological number' but similar initial size]
Control (o); Compact (●)

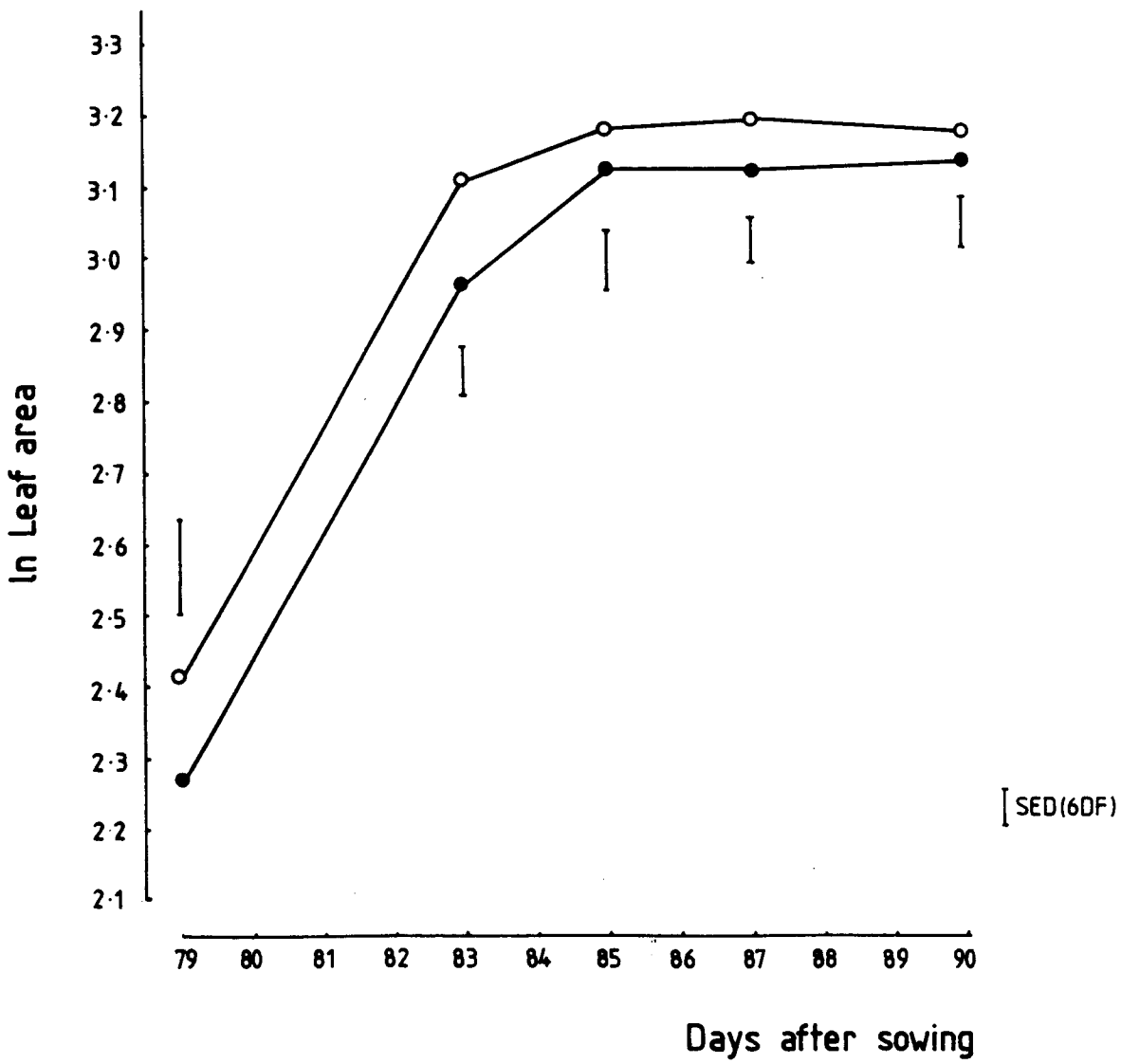
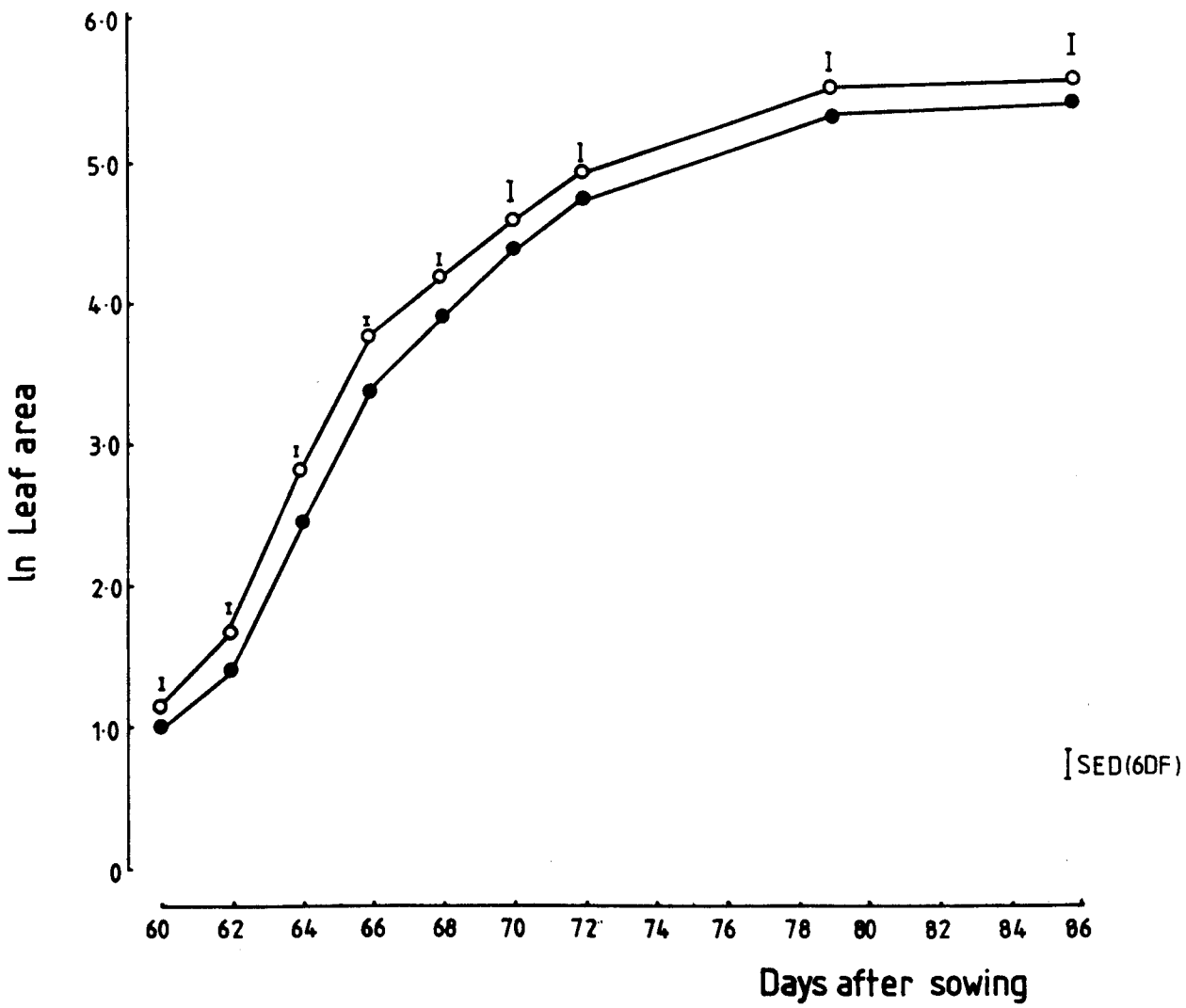

3·3
3·2
3·1
3·0
2·9
2·8
2·7
2·6
2·5
2·4
2·3
2·2
2·1
ln Leaf area
79
80
81
82
83
84
85
86
87
88
89
90
Days after sowing
SED(6DF)

Figure 5.9 The influence of soil compaction on the lamina expansion of a single sugar beet leaf in 1984. [leaves of different 'morphological number' but similar initial size]
Control (o); Compact (●)


6·0
5·0
4·0
3·0
2·0
1·0
0
ln Leaf area
60
62
64
66
68
70
72
74
76
78
80
82
84
86
Days after sowing
SED(6DF)

Research and Education Committee (1982b) reported on the factors influencing the expansion of sugar beet leaves. They found that the first pair of leaves appeared after the crop had experienced an accumulated temperature of 400°C day^{-1} above 0°C from sowing (thermal time) and that each subsequent leaf appeared with each additional 30°C above 0°C. This sequence was thought to occur irrespective of season or agronomy. After unfolding, the leaves expanded linearly with accumulated temperature at a thermal rate which changed with the leaf position but which was unaffected by season or agronomy. By changing the sowing date, crop density or nitrogen status only the length of the expansion period was affected and not the rate of expansion.

Thermal time from sowing is the principal environmental factor which controls the appearance and subsequent development of leaves (Gallagher, 1979). Since both treatments of each crop were sown at the same time it would appear that they should have experienced similar amounts of thermal time. However compaction delayed the emergence of field beans and sugar beet by approximately 4 days (Figure 4.1) while during the emergence period (19-30th April, 1984), the soil temperature at 09.00 hours was approximately 1°C lower than the air temperature (Sutton Bonington Agrometeorological Station Records, 1984). This small difference in the thermal time of 4°C d is unlikely to be totally responsible for the reduced leaf expansion in the compact treatment.

Visual inspection showed that soil compaction had delayed the emergence but not the germination of the seedlings, an observation which was confirmed by the findings of Prihar and Chowdhary (1977). Furthermore Goss (1974), using a system of ballotini beads to simulate the growth medium and by applying an external pressure 0.1 MPa, found that

leaf expansion can be severely restricted by mechanical impedance of the shoot. In addition, Milford (1982) reported 'evidence that processes early in leaf development such as the division and expansion of cells in the leaf primordia, may determine how soon the leaf area starts to expand linearly with temperature'.

It therefore seems possible that the small reduction in the length of the environmental stimulus (thermal time), coupled with the mechanical restriction to initial leaf development brought about by soil compaction, may have caused the restriction to leaf expansion which was observed in the compact treatments of field bean and sugar beet crops at the beginning of the season.

The reported effects of water stress on leaf expansion (Karamanos, 1978; Hebblethwaite, 1982; Dantuma, Von Kittlitz, Frauen and Bond, 1983) cannot be disregarded in connection with soil compaction and these will be discussed in Chapter 9.

5.3.3 Light Interception

The equations used in the calculation of fractional light interception and absorption of radiation by the crop canopy are given in Appendix 4.

5.3.3.1 Photographic measurements

The foliage cover, that is the fraction of the ground covered by foliage, was measured from photographs taken vertically above the crop in 1984. Examples of these photographs, showing the effect of soil compaction on the foliage cover of field beans (at 79 days after sowing), spring barley (at 79 days after sowing) and sugar beet (at 76 days after sowing) are shown in Plate 5.1.

Plate 5.1 The influence of soil compaction in 1984 on the foliage cover of:

a) field beans at 79 days after sowing
b) spring barley at 79 days after sowing
c) sugar beet at 76 days after sowing

A)

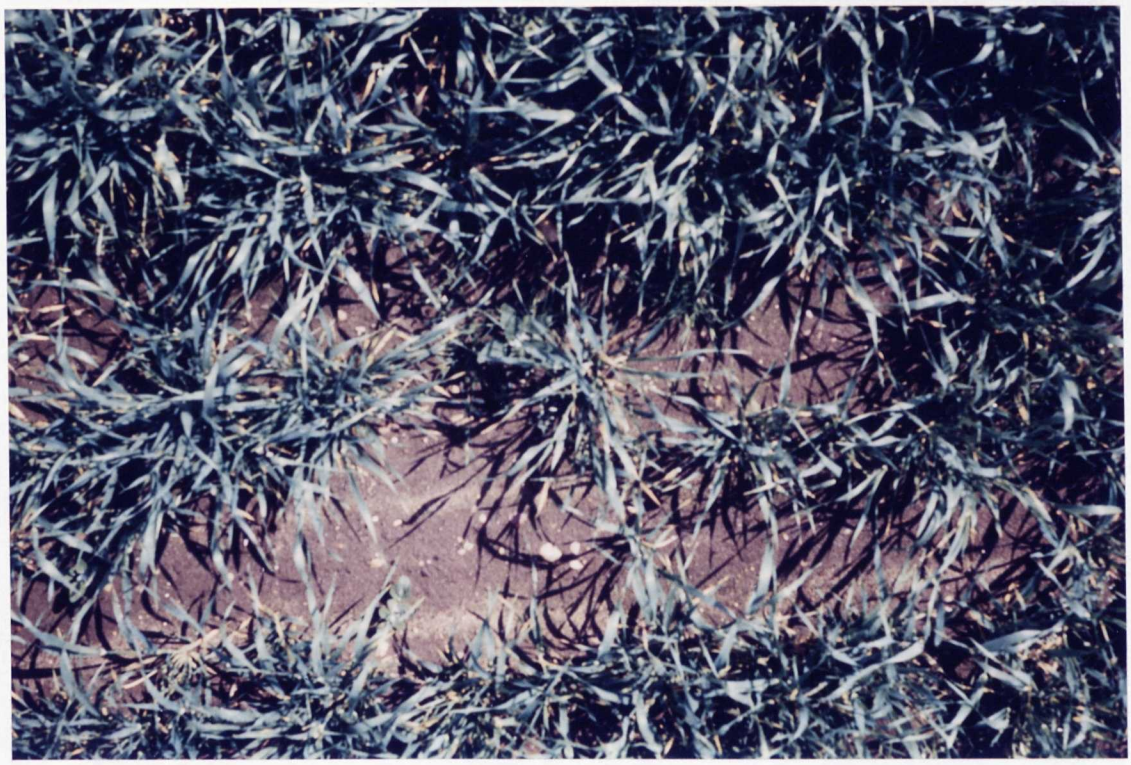
CONTROL

COMPACT

B)

CONTROL

COMPACT



C)

CONTROL

COMPACT

The tube solarimeters give a poor estimate of the light intercepted by a young crop and therefore photographic measurements of foliage cover were used as a surrogate for solarimeter data in the analysis of light interception at the beginning of the growing season. Foliage cover and light interception have been found to be almost equal in field beans and in sugar beet but foliage cover is always greater than interception in barley (Stevens et al., 1985). The corrections required to determine the approximate light interception from measurements of foliage cover are given in Appendix 5.

Soil compaction reduced significantly the fraction of light intercepted by each crop during the establishment of the leaf canopy (Figure 5.10). This was largely a result of a lower plant population and a smaller individual leaf size in the compact treatment than in the control.

5.3.3.2 Solarimeter measurements

The fraction of light intercepted by field bean, spring barley and sugar beet crops in 1984, estimated from solarimeter measurements, is given in Figure 5.11.

In field beans, there was a small reduction in the light interception after 65 days after sowing owing to soil compaction. This trend was reversed toward the end of the season when the compact treatment maintained a greater light interception than the control. This may have been a result of the delayed leaf senescence observed in the compact plots which was also evident in the leaf area data (Sub-section 5.3.1).

There was an inconsistency between the photographic and the solarimeter determination of light interception. The results from the

Figure 5.10 The influence of soil compaction on the fraction of light intercepted by field bean (A), spring barley (B) and sugar beet (C) in 1984 as estimated from photographic measurements. Control (o); Compact (●)

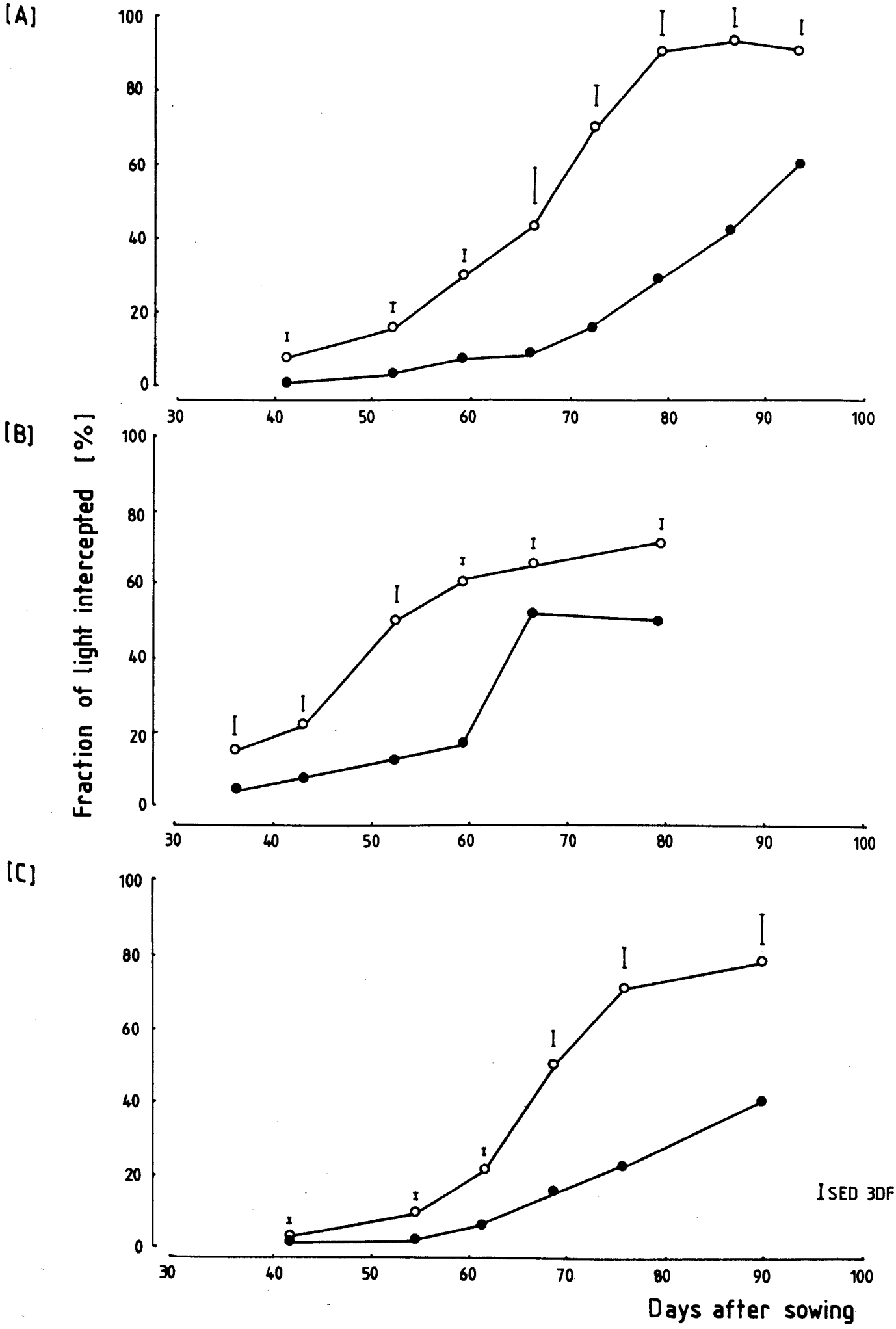
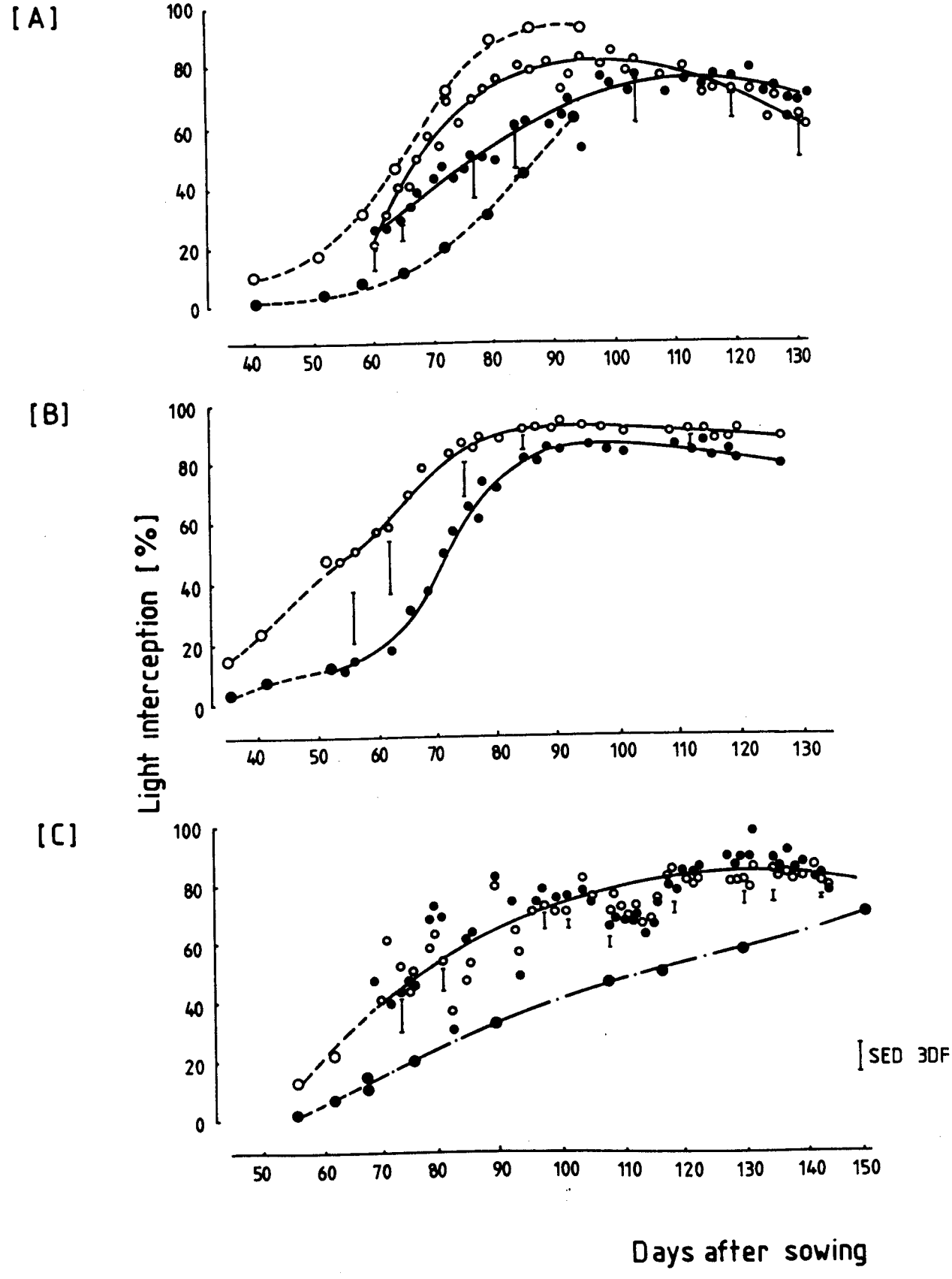

[A]
[B]
[C]
Fraction of light intercepted [%]
100
80
60
40
20
0
30
40
50
60
70
80
90
100
I SED 3DF
Days after sowing

Figure 5.11 The influence of soil compaction on the fraction of light intercepted by field beans (A), spring barley (B) and sugar beet (C) in 1984 as estimated from solarimeter measurements. Control (o); Compact (●) [photographic estimate of fractional light interception (----)]


[A]
[B]
[C]
Light interception [%]
100
80
60
40
20
0
40 50 60 70 80 90 100 110 120 130
50 60 70 80 90 100 110 120 130 140 150
SED 3DF
Days after sowing
[●—·—● COMPACT % LIGHT INTERCEPTION (ESTIMATED)-see Appendix 4]

photographic method suggested that soil compaction reduced significantly the fraction of light intercepted by the crop during the establishment and linear growth phases. However results from the solarimeter method did not show any significant difference in light interception at the beginning of the monitoring period between the treatments. This difference between the two methods may have been due to differences in sample size. The tube solarimeters measured transmitted light over a very small area of the crop leaf canopy and data showed a relatively high coefficient of variation (cv. 23-55%). Whereas the photographic data, averaged over a wide area of the crop, showed a lower coefficient of variation (cv.$<$28%) than the solarimeter data. Furthermore, it is possible that the solarimeters may have overestimated the light which was intercepted because in a sparse crop, such as in the compact treatment, shadows can be produced, when the sun is not directly overhead, from plants which are adjacent to the ends of the instrument. These shadows may have fallen across the solarimeter thus causing an overestimation of the fractional light interception. Shading of this type is not a significant problem in uniform crops of average plant population.

With spring barley, both the photographic and the solarimeter data suggested that soil compaction reduced the light interception throughout the season. The difference between the treatments was largely the result of a reduced leaf area in the compact plots since there was no difference in the rate of increase of the fraction of light intercepted. Both treatments achieved a maximum light interception at anthesis and this was maintained until harvest time. However after anthesis an increasing fraction of light was intercepted by senescent material.

With sugar beet the very low population of the compact treatment caused the tube solarimeter measurements of light interception to be influenced by the position of the instrument in the crop. It resulted in highly variable data and thus the values of light interception had to be estimated from measurements of LAI, using a method which assumed a similar canopy structure for both compact and control treatments (Appendix 4, equations A.2 and A.3). Soil compaction reduced the estimated fraction of light intercepted by the sugar beet crop throughout the season.

5.3.4 Conversion efficiency

The relationship between the total crop dry matter produced, from the first to the last sampling dates and the radiation absorbed over the same period in 1984 is shown for field beans, spring barley and sugar beet in Figure 5.12.

A simple regression analysis was performed on the data and since the dry matter accumulation could not be positive when PAR = 0, the regression line was forced through the origin (Gallagher and Biscoe, 1978). The slope of the line expressed the quantity of dry matter produced for every MJ of PAR absorbed — the conversion efficiency. The photographic estimates of the fractional light interception of spring barley and sugar beet were included in the determination of PAR absorbed for the above analysis. However, there was a poor correlation with field beans between the photographically determined fraction of light intercepted and the tube solarimeter determination of the fraction of light intercepted. Therefore only the latter data was used to calculate the amount of PAR absorbed because light interception for a longer period of the season had been estimated than for the former technique.

Figure 5.12 The effect of soil compaction on the efficiency of dry matter production by field beans (A), spring barley (B) and sugar beet (C) crops in 1984. Control (o); Compact (●)

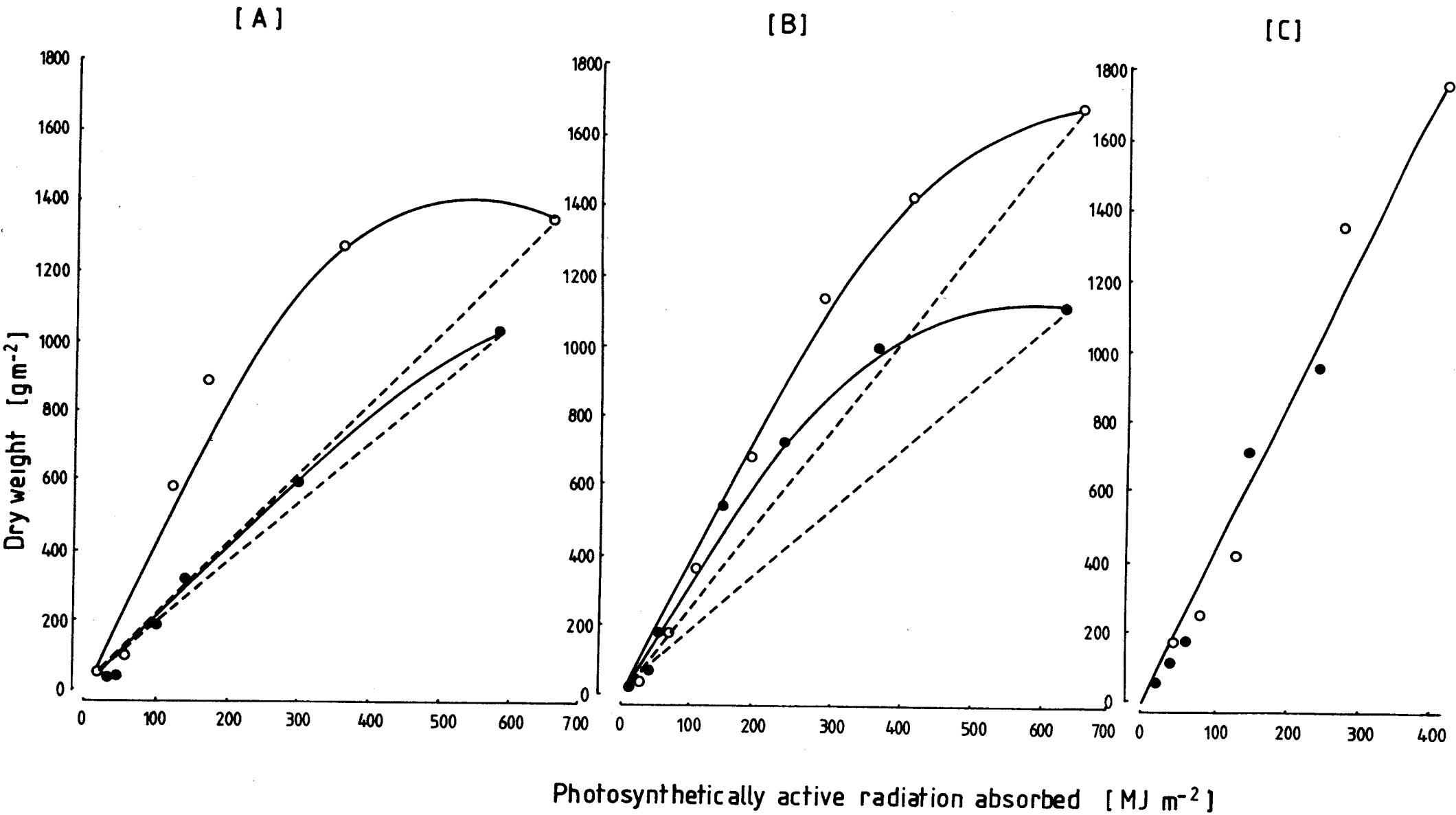

[A]
[B]
[C]
Dry weight [g m-2]
Photosynthetically active radiation absorbed [MJ m-2]
0
200
400
600
800
1000
1200
1400
1600
1800
100
300
500
700

Table 5.2 shows the effect of soil compaction on the maximum conversion efficiency (ε_m), taken as the slope of the line up to anthesis (Figure 5.12). Table 5.2 also shows the mean seasonal efficiency ($\bar{\varepsilon}$), taken as the slope of the line drawn between the origin and the last part of the curve. This includes an estimate of the efficiency during the senescent phase and it is therefore subject to greater uncertainty than measurements of ε_m. The sugar beet crop does not achieve anthesis until its second year of growth and therefore the conversion efficiency (ε_m) was calculated for the slope of the line of best fit through all the points.

There was no significant effect of soil compaction on ε_m of spring barley or of sugar beet or $\bar{\varepsilon}$ of field bean or of spring barley. However the data suggested that soil compaction reduced significantly ($p<0.01$) ε_m of field beans.

Fasheun and Dennet (1982) reported that the field bean crop had an almost constant efficiency of dry matter production throughout the season, when grown under optimal conditions. However the conversion efficiency of the control treatment declined at the end of the season as the crop senesced, while that of the compact treatment remained constant. This resulted in a similar $\bar{\varepsilon}$ for both treatments and suggested that the compact treatment was not stressed after anthesis.

Why then should compaction have reduced ε_m and not reduced $\bar{\varepsilon}$. After careful examination of the photographs of the foliage cover up to 90 days after sowing it was concluded that the tube solarimeters had overestimated the fractional light interception of the compact treatment, before anthesis. The possible explanations for this overestimation were discussed in the previous sub-section.

Table 5.2 The effect of soil compaction on the conversion efficiency of field beans, spring barley and sugar beet in 1984

	CONVERSION EFFICIENCY (g MJ^{-1})			
	Control	Compact	SED (D.F)	Sig*
FIELD BEAN				
ε_m (solarimeter)	3.76	1.87	0.26 (6)	$p<0.01$
ε_m (photographic)	3.97	3.58	0.39 (12)	NS
$\bar{\varepsilon}$	1.97	1.69	0.15 (3)	NS
SPRING BARLEY				
ε_m	3.56	3.89	0.17 (12)	NS
$\bar{\varepsilon}$	2.50	1.75	0.12 (3)	NS
SUGAR BEET				
ε_m	4.59	4.47	0.20 (14)	NS

* level of statistical significance

ξ_m of the field bean crop was recalculated using the photographic estimate of fractional light interception to determine the PAR absorbed. There was found to be no significant reduction in ξ_m due to soil compaction (Table 5.2).

It is essential to note, when comparing the conversion efficiencies of the treatments, that no account was made of the root weight in the total dry matter measurements. This is generally considered to be a constant fraction of the total dry matter (McGowan, M., personal communication, 1984) and has not been found to be reduced by mechanical impedance (Barley, 1965; Goss and Russell, 1980).

The values of ξ_m for the crops reported in Table 5.2 are similar to those found for field bean (4.1 g MJ^{-1}) by Fasheun and Dennett (1982) and slightly greater than that found for cereals (3.0 g MJ^{-1}) by Gallagher and Biscoe (1978) and for sugar beet (3.5 g MJ^{-1}) by Biscoe and Gallagher (1977). The value of $\bar{\xi}$ for spring barley was found to be similar to that reported (2.2 g MJ^{-1}) by Gallagher and Biscoe (1978).

The conversion efficiency of the leaf canopy is lower after anthesis because no new leaves are produced and the photosynthetic activity of the existing leaves declines with age (Biscoe, Scott and Monteith, 1975). Furthermore, respiration per unit of assimilate tends to increase after anthesis which results in a reduced amount of dry matter produced from photosythesis (Biscoe, Scott and Monteith, 1975).

The results reported in this chapter suggest that the principal effect of soil compaction on the production of dry matter by the crop was to reduce the LAI and thus the fractional light interception of the leaf canopy.

Chapter 6

ROOT GROWTH

6.1 Introduction

The growth of roots to a depth which assures an adequate supply of water and nutrients may be one of the major requirements for the survival of crops (Goss, 1977). Deep rooting depends on the presence of a sufficient number of continuous pores through which roots can penetrate. Circumnutational movements exist which may aid the root tip in locating voids (Fisher, 1964) but roots are incapable of decreasing in size to enter pores of a smaller diameter than themselves (Wiersum, 1957). Therefore, considerable inhibition of root extension may occur in compacted soils if the pore size has been reduced to a diameter less than that of the root.

This chapter considers the analysis of the length, weight and distribution of roots grown in compacted soil and it is therefore crucial to the understanding of how plant growth is affected by mechanical stress.

6.2 Materials and Methods

6.2.1 Root Length

The measurement of root length has always been considered to be tedious and time-consuming. Even with the introduction of automated methods (Rowse and Phillips, 1974; Richards, Gaubran, Garwoli and Doly, 1979), the root length of a topsoil sample can take at least 4 hours to measure. Most of the time is taken in washing the roots free of soil and in

hand-sorting live roots from organic debris. However McGowan, Armstrong and Corrie (1983) recently developed a rapid fluorescent-dye technique for measuring root length which reduced the washing and cleaning time to approximately ten minutes per sample.

This method is based on the observations of Wildholm (1979), that fluorescein diacetate could be used to distinguish between live and dead cells in cell suspension cultures. McGowan et al. (1983) reasoned that root length could be determined by taking photographs of the fluorescing roots under Ultra Violet light and by measuring the length of the fluorescent image on the negative, using the line intersection method of Newman (1966).

The McGowan et al. (1983) technique was employed to measure the length of roots washed from Jarret auger core samples, taken at 10 cm (811 cm^3) increments to 30 cm depth and 20 cm increments to 90 cm depth (1983). In 1984, cores were taken at 10 cm (811 cm^3) increments to the approximate maximum rooting depth, calculated from neutron probe data at the time of measurement. A stock solution of flourescein diacetate was prepared by dissolving 0.5 g of dye in 100 ml acetone and stored at 1°C. The root samples were washed from the soil and suspended in water. They were then stirred and the organic debris was floated off the surface. The sample was again stirred and then strained three times before the roots were placed in a 10% dilution of the dye in a glass petri dish. After 30 minutes they were washed on a 200 µm sieve and then floated onto a 50 cm x 30 cm tension table fitted with a black sugar-paper filter. The roots were evenly distributed using forceps and a water jet before applying a suction which forced them onto the sugar-paper. The tension table was then transferred to a 'light-box' and exposed to two Ultra Violet light

sources: a short-wave (254 nm) low pressure mercury vapour discharge tube (Camlab UVS54 Mineralight) and a medium pressure, 365 nm mercury vapour lamp (Hanovia Model II). The exposure time for black and white Ilford FP4 (125 ASA) film was 45 secs. The film was later developed and the negatives were projected onto a grid. The number of root intersections were manually counted and converted to an estimate of root length (Newman, 1966).

The method is simple and fast and does identify live roots. The inclusion of weed roots was partially offset by incomplete crop root recovery. However, care must be taken to spread the well-branched root system as uniformly as possible on the tension table. The errors associated with this method are discussed by McGowan et al. (1983).

The fluorescence of field bean root tissue was prevented by phenolic blackening of the root surface and a mechanised line intersection method (Rowse and Phillips, 1974) was used to measure the root length in 1983. In 1984 the field bean root samples were treated with a 10% solution of Diethyldithiocarbonic acid sodium salt for 20 minutes, which inhibited the phenolic reaction and permitted the dye technique to be used. (Norton, G., personal communication, 1984).

6.2.2 Root Weight

The dry weight of field bean roots, recovered from the mechanised root counter, was measured in 1983 in an aerated oven at 80°C for 48 hours. There was insufficient time to measure the root dry weight of other crops.

6.2.3 Root Distribution

The distribution and depth of roots in the profile was recorded in both years. Pits were dug to a depth of 1 m (Plate 6.1) and the profile face, perpendicular to the plot length, was carefully excavated while water jets were used to reveal the roots. The rooting pattern was first traced onto a perspex sheet, then retraced onto transparent paper and finally photo-reduced in the laboratory. Quantitative analysis was not made of this data and therefore the tracings were not replicated.

The root length, depth and distribution data were not collected for the grass crop.

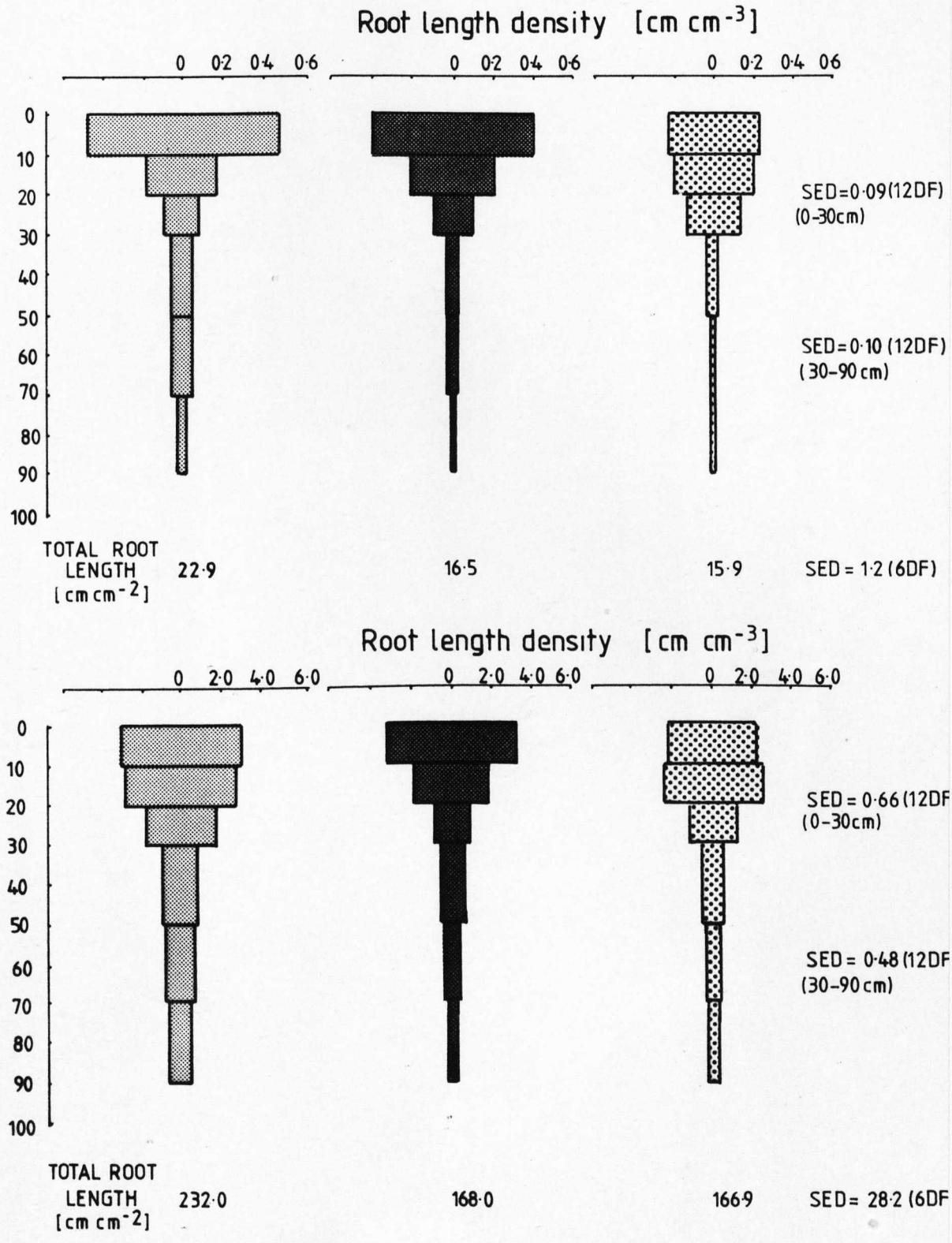
6.3 Results and Discussion

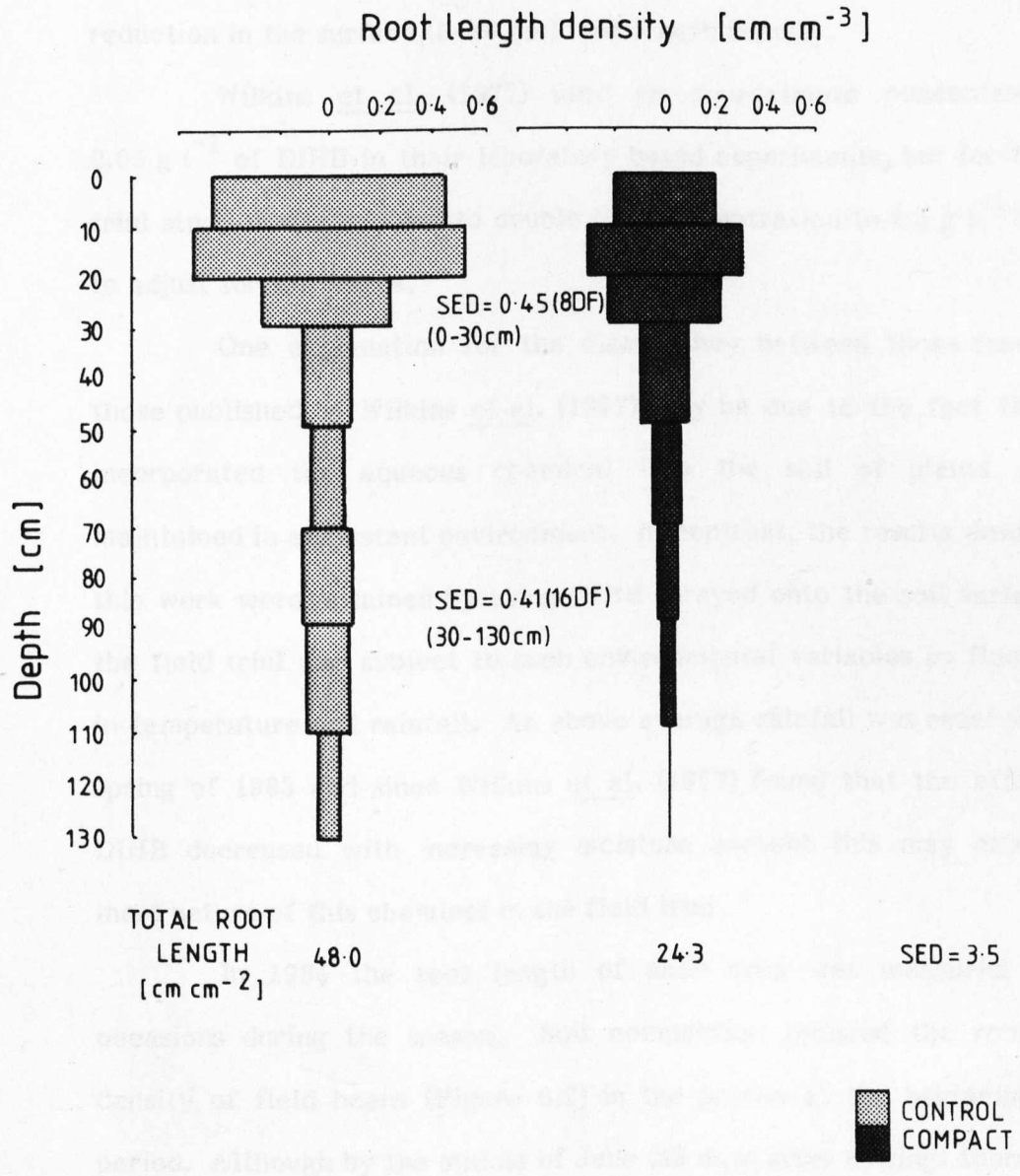
6.3.1 Root Length

The distribution of root length within the soil profile in 1983 is shown in Figure 6.1. Compaction consistently reduced the root length density at each depth in the field beans and in the sugar beet but increased surface rooting (0-10 cm) in the spring barley. This may have been a result of an enhanced development of lateral roots in the compacted layer, as reported by Barley (1962) and Schuurman (1965). The total profile root lengths (cm cm^{-2}) of field beans, spring barley and sugar beet were reduced by 28%, 27% and 49% respectively, owing to soil compaction. However, even in compact soil, the spring barley achieved a total of 168.0 cm cm^{-2} of roots compared with 22.9 cm cm^{-2} for field beans and 48.0 cm cm^{-2} for sugar beet in non-compacted soils.

Plate 6.1 The excavated soil profile face under spring barley before tracings of root distribution were made

Figure 6.1 Root length density profiles of field beans (123 days after sowing), spring barley (129 days after sowing) and sugar beet (132 days after sowing) as influenced by control, compact and DIHB treatments in 1983


Root length density [cm cm-3]
0 0·2 0·4 0·6
0 0·2 0·4 0·6
0 0·2 0·4 0·6
0
10
20
30
40
50
60
70
80
90
100
SED=0·09(12DF)
(0-30cm)
SED=0·10 (12DF)
(30-90 cm)
TOTAL ROOT LENGTH [cm cm-2]
22·9
16·5
15·9
SED = 1·2 (6DF)
Root length density [cm cm-3]
0 2·0 4·0 6·0
0 2·0 4·0 6·0
0 2·0 4·0 6·0
0
10
20
30
40
50
60
70
80
90
100
SED = 0·66 (12DF
(0-30cm)
SED = 0·48 (12DF
(30-90 cm)
TOTAL ROOT LENGTH [cm cm-2]
232·0
168·0
166·9
SED= 28·2 (6DF
CONTROL
COMPACT
DIHB


Root length density [cm cm^{-3}]
0 0·2 0·4 0·6
0 0·2 0·4 0·6
Depth [cm]
0
10
20
30
40
50
60
70
80
90
100
110
120
130
SED = 0·45 (8DF)
(0-30cm)
SED = 0·41 (16DF)
(30-130cm)
TOTAL ROOT LENGTH [cm cm^{-2}]
48·0
24·3
SED = 3·5
CONTROL
COMPACT

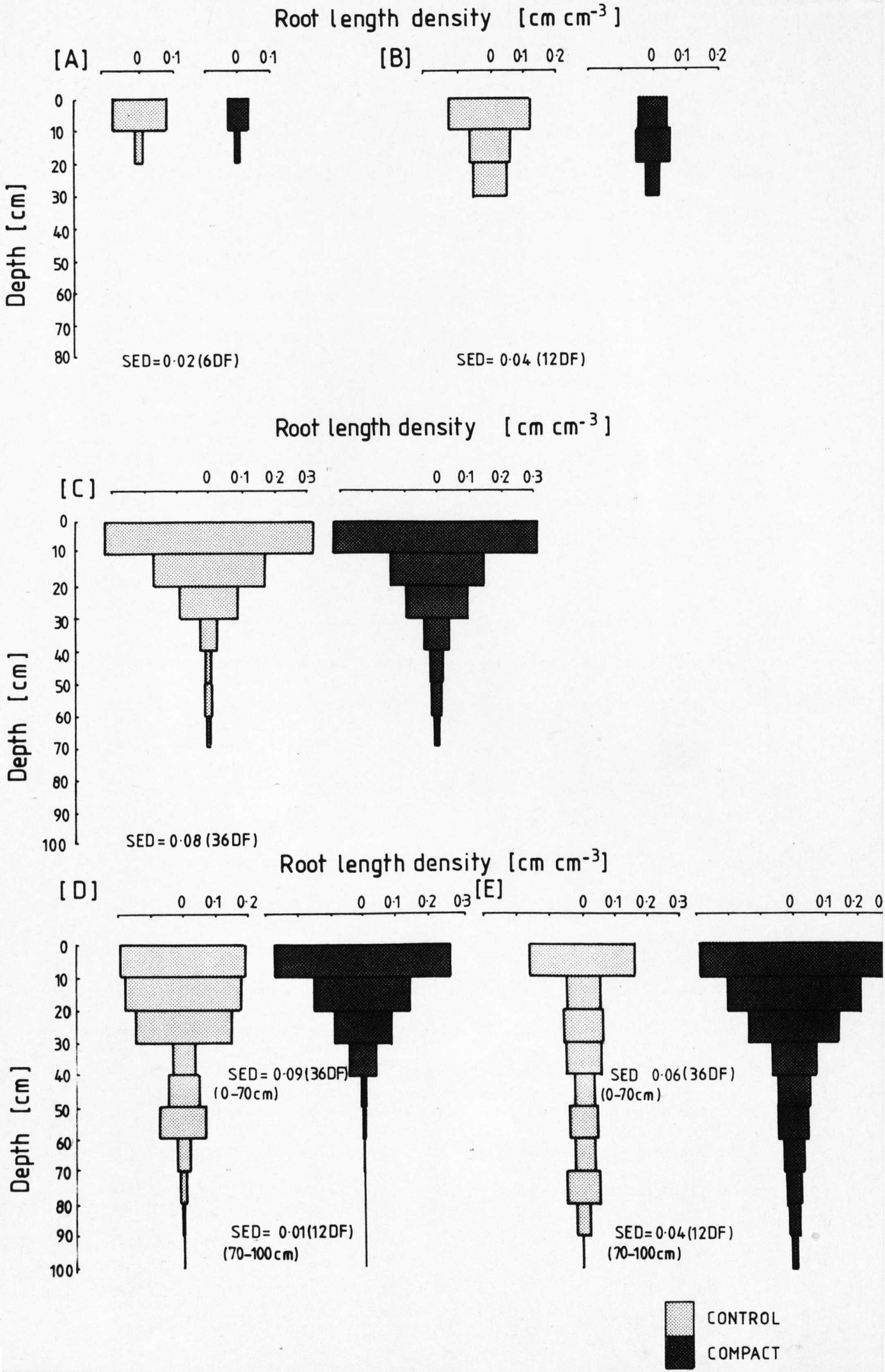
The root length of field beans and spring barley, grown in DIHB treated soil was also measured in 1983 (Figure 6.1). This soil treatment, which was reputedly able to increase the root length of peas by as much as 31% when incorporated into compact soil (Wilkins et al., 1977), did not expand the root system of either crop. The total root length of the DIHB treated crops was no different from that found in compact soil, despite a reduction in the surface (0-10 cm) root length density.

Wilkins et al. (1977) used an approximate concentration of 0.05 g l^{-1} of DIHB in their laboratory based experiments, but for the field trial study it was decided to double this concentration to 0.1 g l^{-1} in order to adjust for soil losses.

One explanation for the discrepancy between these results and those published by Wilkins et al. (1977) may be due to the fact that they incorporated the aqueous chemical into the soil of plants in pots, maintained in a constant environment. In contrast, the results described in this work were obtained by using DIHB sprayed onto the soil surface, and the field trial was subject to such environmental variables as fluctuations in temperature and rainfall. An above average rainfall was received in the spring of 1983 and since Wilkins et al. (1977) found that the efficacy of DIHB decreased with increasing moisture content this may explain the inert nature of this chemical in the field trial.

In 1984 the root length of each crop was measured on five occasions during the season. Soil compaction reduced the root length density of field beans (Figure 6.2) in the profile at the beginning of the period. Although by the middle of June (83 days after sowing) there was no difference in the root length distribution, only one month later (114 days after sowing) compaction had restricted the majority of roots to the top

Figure 6.2 The effect of soil compaction on the root length density of field beans in the soil profile at: 41 (A), 62 (B), 83 (C), 114 (D) and 137 (E) days after sowing in 1984.


Root length density [cm cm-3]
[A]
0 0·1
0 0·1
[B]
0 0·1 0·2
0 0·1 0·2
Depth [cm]
0
10
20
30
40
50
60
70
80
SED=0·02(6DF)
SED= 0·04 (12DF)
Root length density [cm cm-3]
[C]
0 0·1 0·2 0·3
0 0·1 0·2 0·3
0
10
20
30
40
50
60
70
80
90
100
Depth [cm]
SED = 0·08 (36DF)
Root length density [cm cm-3]
[D]
0 0·1 0·2
0 0·1 0·2 0·3
[E]
0 0·1 0·2 0·3
0 0·1 0·2 0
0
10
20
30
40
50
60
70
80
90
100
Depth [cm]
SED= 0·09(36DF)
(0-70cm)
SED= 0·01(12DF)
(70-100cm)
SED 0·06(36DF)
(0-70cm)
SED= 0·04(12DF)
(70-100cm)
CONTROL
COMPACT

40 cm of soil, but there was only a small reduction in the total root length. This feature substantiates the observations of Russell (1968) who found that root systems displayed a large compensatory capacity. By the beginning of August (137 days after sowing) the compacted field bean crop had developed a larger root system than the control, at all depths above 70 cm. It is possible that this was a consequence of the delayed senescence, observed in compact field bean and spring barley crops late in the season, as indicated by an increase in water use, relative to the control (Chapter 7). There may have been a similar length of roots in the soil of both treatments but since the flourescein diacetate stain is only taken up by 'live' roots, the senesced roots of the control crop would not have been recorded.

Concern has been expressed over the value of the rapid fluorescent-dye technique because it consistently measures lower root lengths than the mechanised method (Hector, D., personal communication, 1985). However, because the technique measures 'live' and hence active roots, it can be related to crop water use more accurately than existing methods of root length analysis.

In 1984 it was observed that the root length density of spring barley (Figure 6.3) was reduced within the soil profile by compaction until the end of July (133 days after sowing) when a greater rooting density was observed in the surface 40 cm of compact soil. The possible causes of an apparently greater rooting density in the compact treatment at the end of the growing season have been discussed previously.

Compaction reduced the root length density of the sugar beet crop down the soil profile (Figure 6.4) at each observation except in the middle of July (101 days after sowing). This feature is not consistent with

Figure 6.3 The effect of soil compaction on the root length density of spring barley in the soil profile at: 41 (A), 62 (B), 83 (C), 111 (D) and 133 (E) days after sowing in 1984.

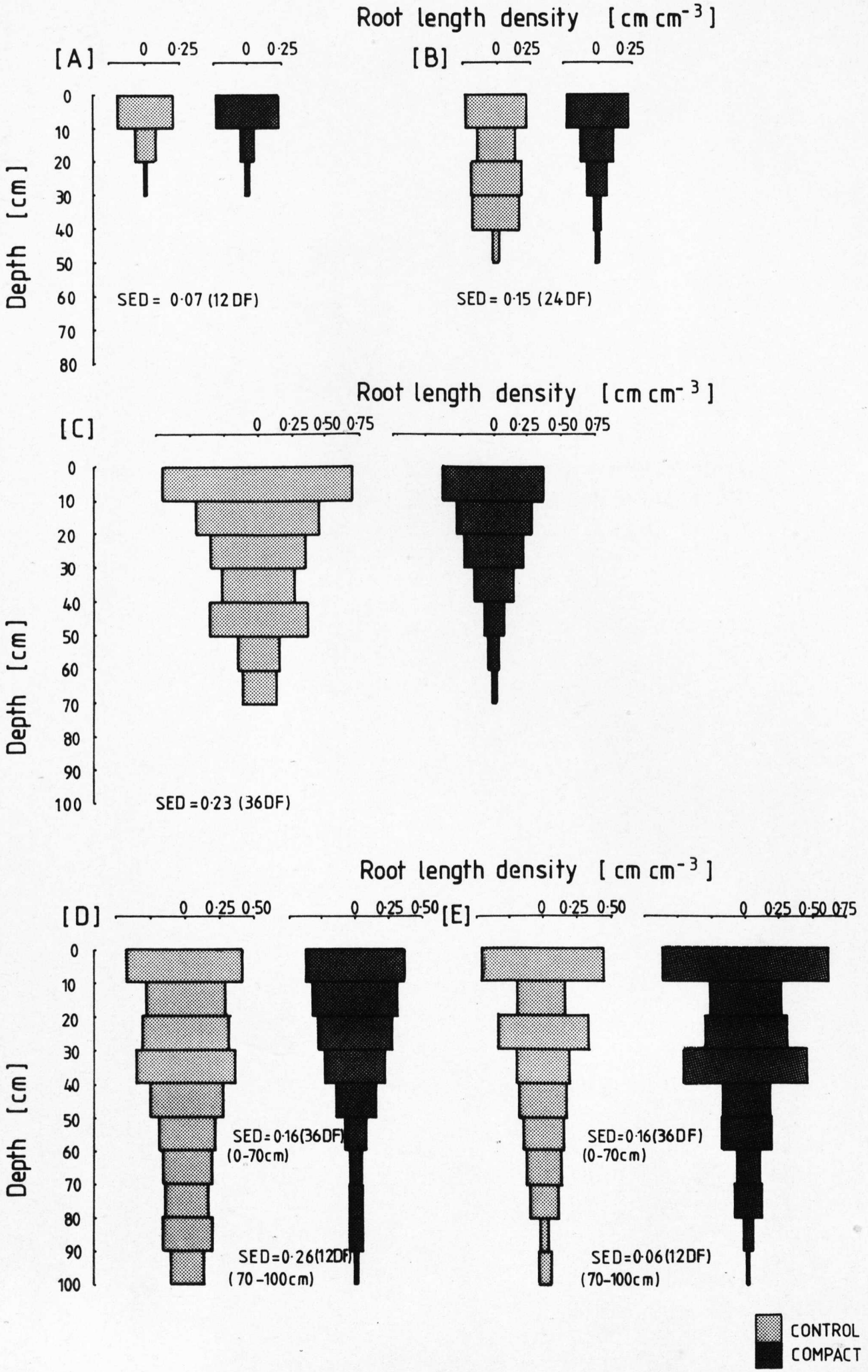
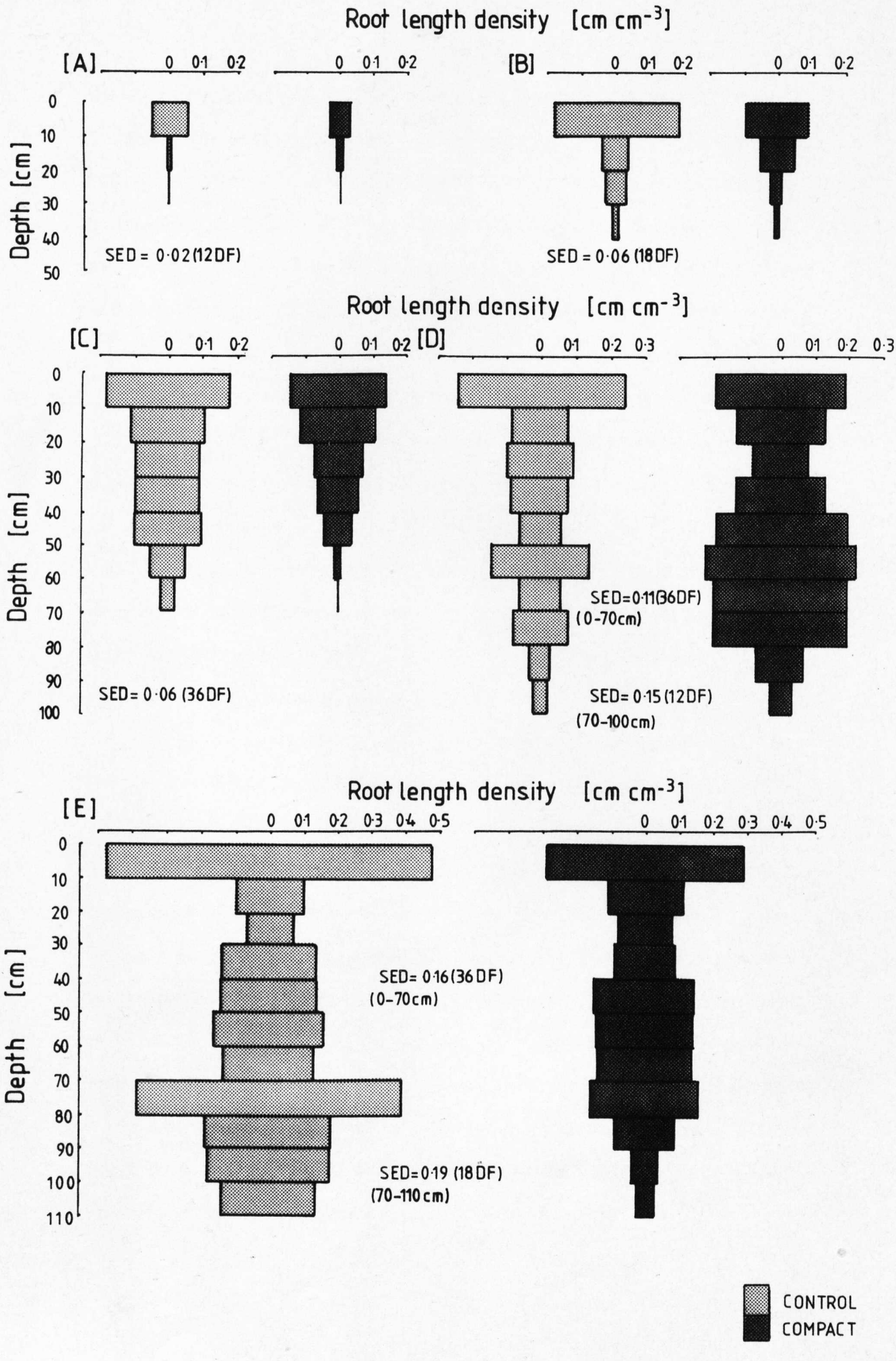

Root length density [cm cm⁻³]
[A]
0 0·25
0 0·25
[B]
0 0·25
0 0·25
Depth [cm]
0
10
20
30
40
50
60
70
80
SED = 0·07 (12 DF)
SED = 0·15 (24 DF)
Root length density [cm cm⁻³]
[C]
0 0·25 0·50 0·75
0 0·25 0·50 0·75
Depth [cm]
0
10
20
30
40
50
60
70
80
90
100
SED = 0·23 (36 DF)
Root length density [cm cm⁻³]
[D]
0 0·25 0·50
0 0·25 0·50
[E]
0 0·25 0·50
0 0·25 0·50 0·75
Depth [cm]
0
10
20
30
40
50
60
70
80
90
100
SED = 0·16 (36 DF)
(0–70 cm)
SED = 0·26 (12 DF)
(70–100 cm)
SED = 0·16 (36 DF)
(0–70 cm)
SED = 0·06 (12 DF)
(70–100 cm)
CONTROL
COMPACT

Figure 6.4 The effect of soil compaction on the root length density of sugar beet in the soil profile at: 40 (A), 59 (B), 80 (C), 101 (D) and 124 (E) days after sowing in 1984.


Root length density [cm cm-3]
[A]
0 0·1 0·2
0 0·1 0·2
[B]
0 0·1 0·2
0 0·1 0·2
Depth [cm]
0
10
20
30
40
50
SED = 0·02 (12 DF)
SED = 0·06 (18 DF)
Root length density [cm cm-3]
[C]
0 0·1 0·2
0 0·1 0·2
[D]
0 0·1 0·2 0·3
0 0·1 0·2 0·3
Depth [cm]
0
10
20
30
40
50
60
70
80
90
100
SED = 0·06 (36 DF)
SED = 0·11 (36 DF)
(0-70 cm)
SED = 0·15 (12 DF)
(70-100 cm)
Root length density [cm cm-3]
[E]
0 0·1 0·2 0·3 0·4 0·5
0 0·1 0·2 0·3 0·4 0·5
Depth [cm]
0
10
20
30
40
50
60
70
80
90
100
110
SED = 0·16 (36 DF)
(0-70 cm)
SED = 0·19 (18 DF)
(70-110 cm)
CONTROL
COMPACT

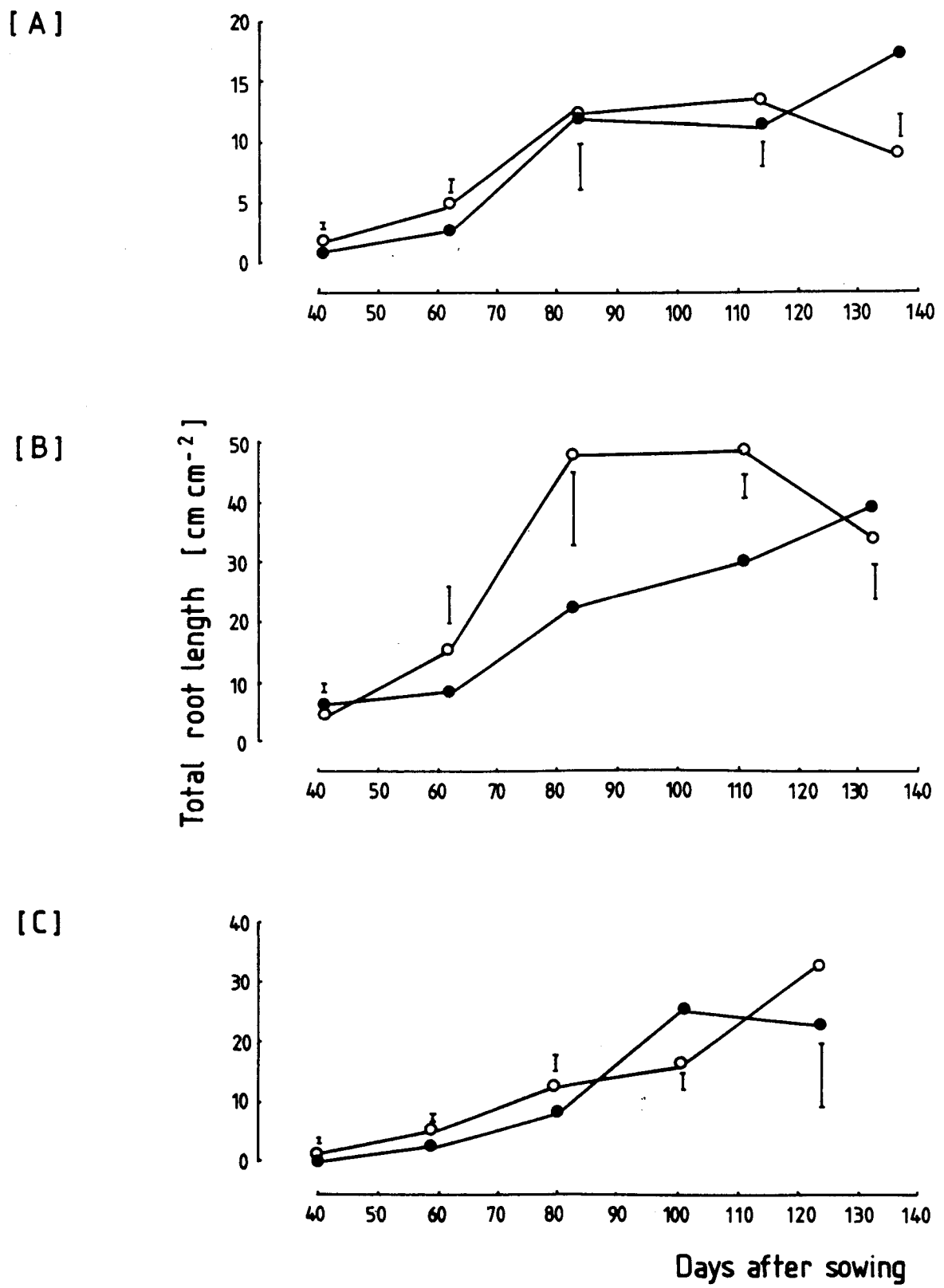
the expected trend and no physiological explanation is at present known. However, the root distribution of the compact crop was probably not uniform throughout the plot because individual plants compensated in growth for the reduced plant population. This may have resulted in a high root length density close to the plants but fewer roots in the soil between the rows. It thus illustrates the problems of achieving a representative sample from a non-uniform crop.

Despite neutron-probe evidence (Chapter 7) to the contrary, compaction did not reduce the maximum depth of rooting but it did diminish the amount of deep roots in all crops.

The change in total root length throughout the 1984 season is given in Figure 6.5. The large errors, inherent in most root investigations, precluded the identification of any significant differences but there was a trend for compaction to lower the total root length of field beans, barley and sugar beet for most of the growing season.

All the measurements of root length made in 1984 appeared to be low in comparison with other data. The maximum total root length recorded for barley in 1984 was only 49.0 cm cm^{-2} compared with 232 cm cm^{-1} in 1983 and 126 cm cm^{-2} for barley roots measured with a mechanised counter (Welbank, Gibb, Taylor and Williams, 1972). After careful examination it appeared that the roots of all the crops did not take up the stain as well in 1984 as in the previous year. The reason for this is uncertain. However, for the purpose of this experiment, treatment comparisons of root length were more critical than absolute values and therefore the data remained valuable. Further work is required to investigate, over a number of years and crops, the consistency of readings taken by using the rapid fluorescent-dye technique.

Figure 6.5 The effect of soil compaction on the total root length of field beans (A), spring barley (B) and sugar beet (C) in 1984. Control (o); Compact (●)


[A]
[B]
[C]
Total root length [cm cm-2]
0
5
10
15
20
30
40
50
60
70
80
90
100
110
120
130
140
Days after sowing
SED (3DF)

6.3.2 Root Dry Weight

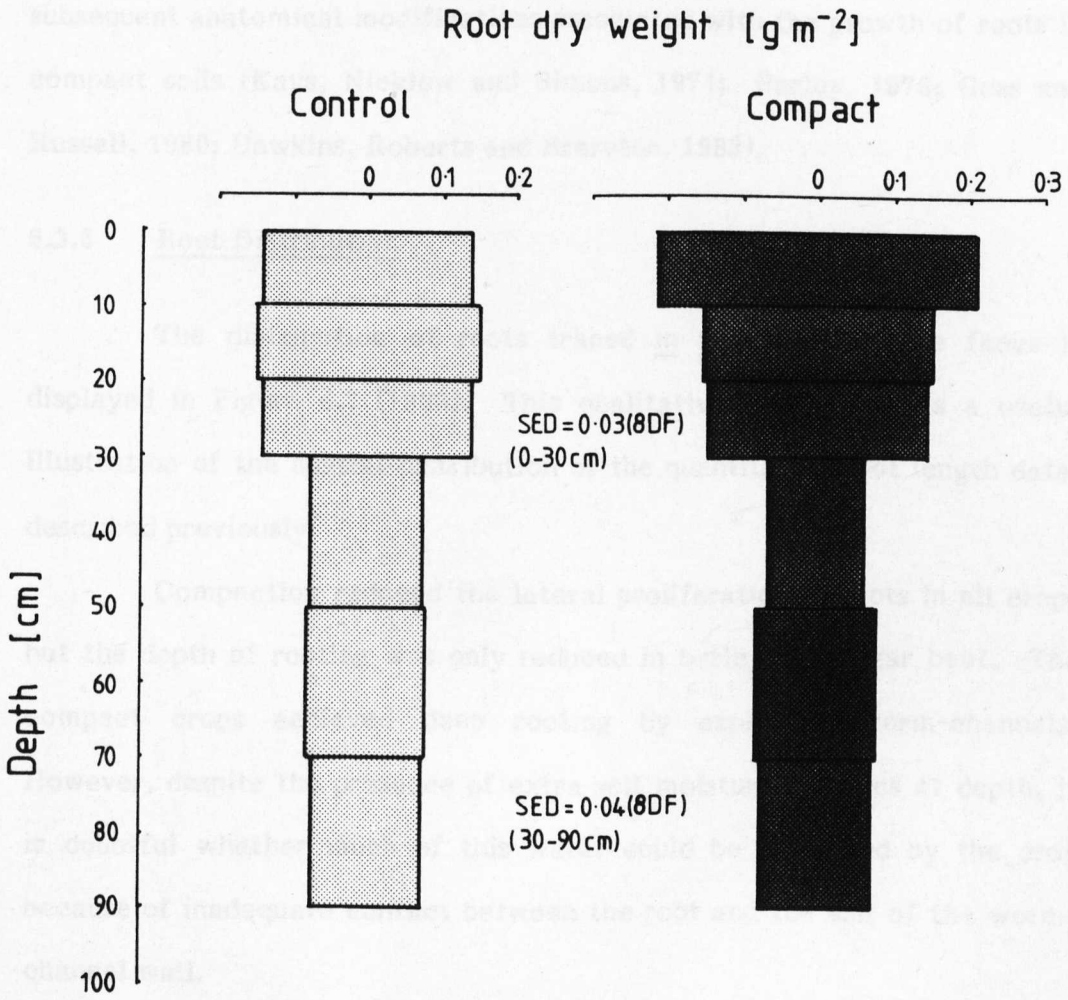
In 1983 the field bean roots were measured by the mechanised line intersection technique (Rowse and Phillips, 1974) and thus the sample, which was relatively free from debris, was saved for dry weight determination.

Compaction caused a small increase in the dry weight of roots in the surface layer (0-10 cm) but the distribution pattern was similar to that found for root length and there was little difference between treatments (Figure 6.6).

Many researchers have observed a decrease in the root length of plants subjected to mechanical impedance but no corresponding decrease in root dry weight (Barley, 1965; Goss and Russell, 1980; Dawkins, 1982). This is because mechanical impedance decreased the longitudinal growth of roots (Barley, 1962; Taylor and Ratliff, 1969; Russell and Goss, 1974) but increased the root diameter (Russell and Goss, 1974; Peterson and Barber, 1981). In very strong soils, Barley (1976) observed a radial enlargement of three times the normal diameter. Wilson, Robards and Goss (1977) found that an external pressure of 20 kPa halved the elongation of barley roots but almost doubled the volume of the cells within 10 cm of the apex. They attributed these changes to an increased number of 'cross-sectional' cortical cells and a larger diameter and volume of the outer cortical and epidermal cells.

It is therefore pertinent to review briefly the theories concerned with the mechanisms of root penetration in compact soil. It was widely assumed that the reduction in the rate of root extension was a direct consequence of an external pressure restricting the elongation of

Figure 6.6 The influence of soil compaction on the distribution of field bean root dry weight in the profile, at 123 days after sowing in 1983


Root dry weight [g m⁻²]
Control
Compact
0
0·1
0·2
0·3
Depth [cm]
0
10
20
30
40
50
60
70
80
90
100
SED = 0·03 (8DF)
(0-30 cm)
SED = 0·04 (8DF)
(30-90 cm)

vacuolating cells. This theory became obsolete when it was found that root extension could be affected by very small external pressures (Barley, 1965). Greacen and Oh (1972) then proposed that mechanical impedance reduced the ability of roots to osmoregulate 'efficiently'. However Kibreab (1975) proved that the osmoregulation of radish roots, which were sensitive to compaction, was not affected by mechanical stress. More recently endogenous ethylene has been implicated in the primary response and in the subsequent anatomical modifications associated with the growth of roots in compact soils (Kays, Nicklow and Simons, 1974; Barley, 1976; Goss and Russell, 1980; Dawkins, Roberts and Brereton, 1983).

6.3.3 Root Distribution

The distribution of roots traced in situ from profile faces is displayed in Figure 6.7 (1983). This qualitative information is a useful illustration of the spatial distribution of the quantitative root length data, described previously.

Compaction reduced the lateral proliferation of roots in all crops but the depth of rooting was only reduced in barley and sugar beet. The compact crops achieved deep rooting by exploiting worm-channels. However, despite the presence of extra soil moisture reserves at depth, it is doubtful whether much of this water could be extracted by the crop because of inadequate contact between the root and the soil of the worm-channel wall.

Compaction resulted in fanging of the sugar beet root and this defect is known to reduce the quality of the marketable product.

In 1984, the depth and distribution of roots, in all crops, were reduced by compaction and fine lateral roots were found to grow in

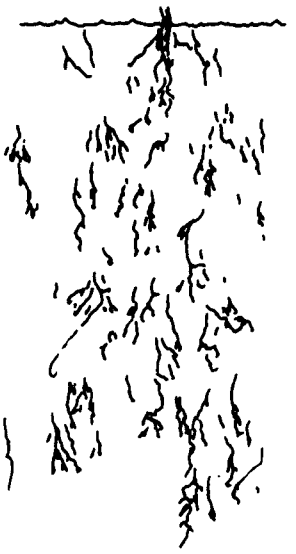
Figure 6.7 The influence of soil compaction on the root distribution of field beans, spring barley and sugar beet, at 138 days after sowing in 1983

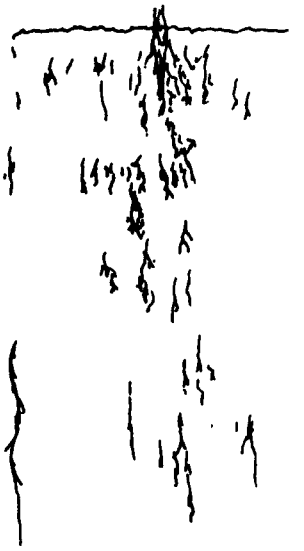
Control

Compact

Depth

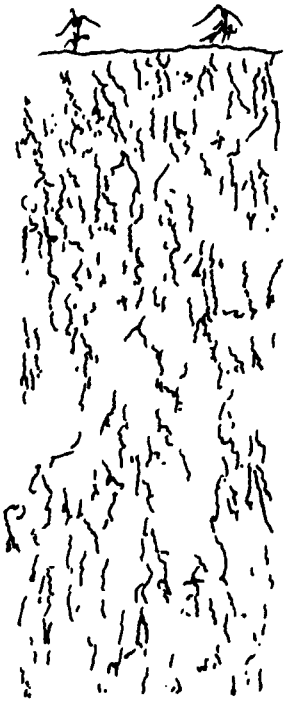
Field bean

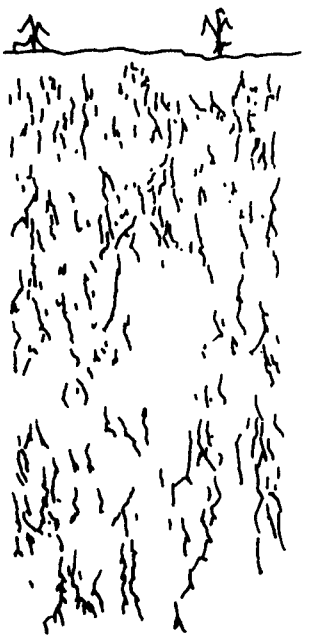




80 cm

Spring barley

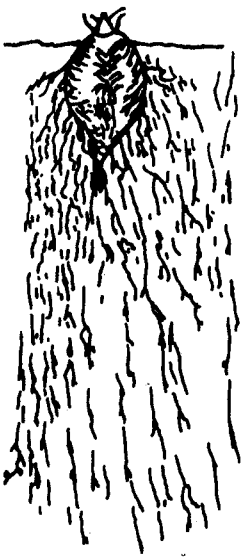




95 cm

100 cm

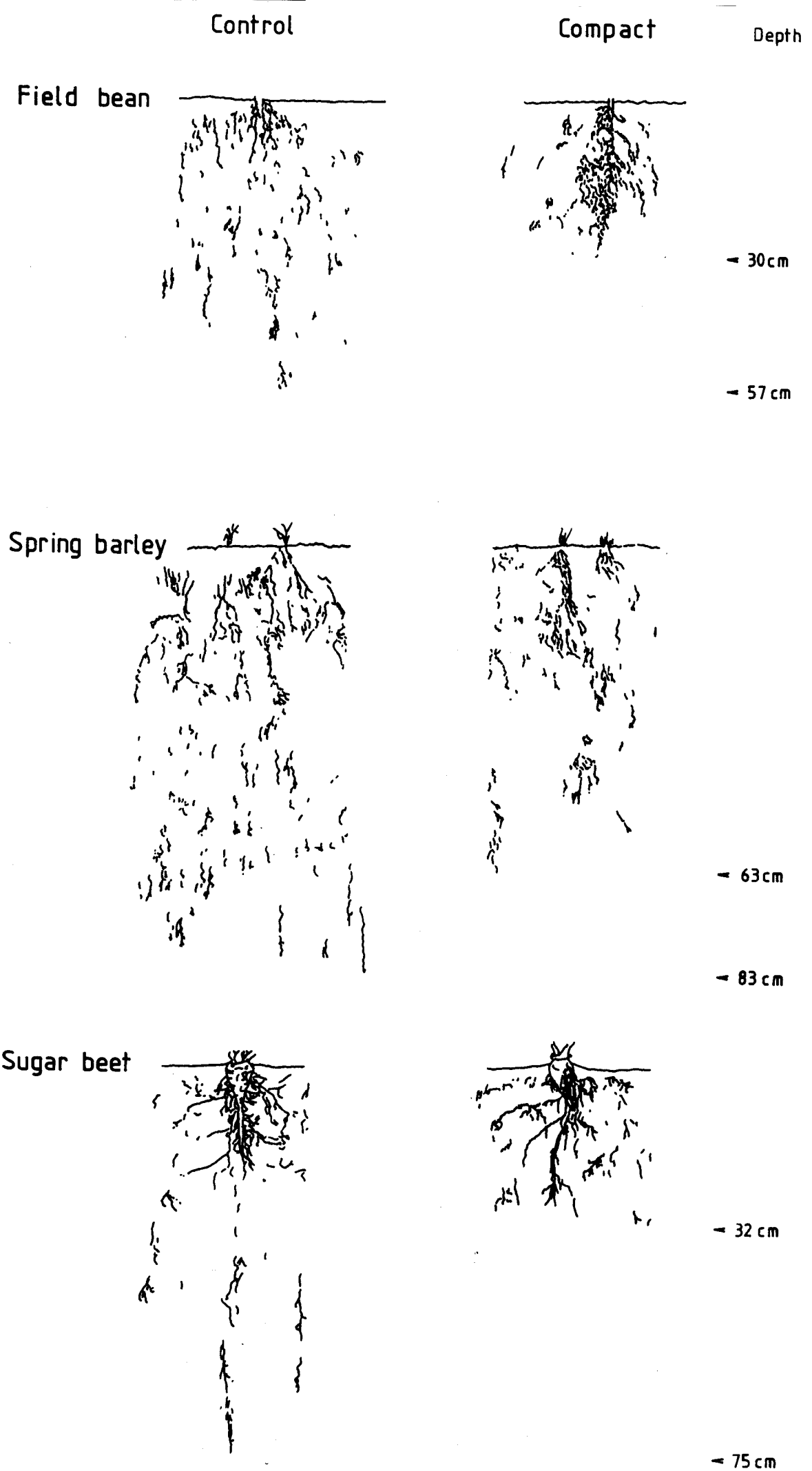
Sugar beet



90 cm

120 cm

Figure 6.8 The influence of soil compaction on the root distribution of field beans and spring barley 108 days after sowing and of sugar beet at 92 days after sowing, in 1984


Control
Compact
Depth
Field bean
30cm
57cm
Spring barley
63cm
83cm
Sugar beet
32 cm
75 cm

clusters in the soil (Figure 6.8). A similar growth habit was observed when the diameter of pores in the rooting medium was intermediate between those of the axes and the laterals (Goss, 1977). The result was an enhanced growth of lateral roots which led to a dense superficial root system. Goss (1977) suggested that this response was similar to that produced when part of the root system was limited by other stresses such as unfavourable temperature, mutilation or dehydration.

Although Goss (1977) did not report that the root apex, in his experiment, was damaged, Wilson and Robards (1979) found that the root cap was generally smaller in a compacted medium, due to a loss of peripheral cells and for this reason it did not give the same degree of protection as an unrestricted root cap. They also reported that mechanical impedance had reduced the number of amyloplasts and starch grains per amyloplast in the columella. It is therefore possible that damage to the root tip, caused by mechanical impedance, may have been sufficient to reduce the degree of apical dominance and thus increase the growth of the lateral roots.

It is interesting to note that the superficial root system observed by Goss (1977) did not affect plant growth provided that sufficient reserves of nutrients and water were available within the root zone.

In both years the order of increasing sensitivity of the root distribution to soil compaction was spring barley, field beans, sugar beet; which follows a similar sequence as the sensitivity of yield to soil compaction.

Chapter 7

SOIL WATER

7.1 Introduction

Many workers have attributed the effects of soil compaction on crop growth to changes in the ability of the root system to supply adequate moisture and nutrients to the plant (Trouse, 1971; Davies, 1975; Hebblethwaite and McGowan, 1980).

Trouse (1971) reviewed the literature on crop water use in compact soils and reported that insufficient moisture to meet the requirements of the crop was the principal causative factor responsible for reduced yield, poor growth and slow development of crops grown in compacted soils. He found that even when compaction was not severe, plant development was often poor because the reduced rate of root elongation into the soil was inadequate to resupply the plant with sufficient water to meet its requirements.

The results of a detailed investigation into the soil water status under grass (1983), field beans, spring barley and sugar beet as influenced by soil compaction in 1983 and 1984 are presented and discussed in this chapter.

7.2 Materials and Methods

7.2.1 Neutron Probe Data

The volumetric water content was measured, using a modified 'Wallingford' neutron probe (Bowman and King, 1966; Bell, 1969, 1973)

every seven days in 1983 and every five days in 1984 from May to September. Aluminium access tubes (42 mm internal diameter) were carefully installed (Williams, 1971; Fry, 1975; McGowan and Williams, 1980) in three replicates of each treatment using a hand-auger and a pneumatic hammer. The tubes were located 1 m from the edge of the plot and they were monitored every 10 cm to a depth of 150 cm (field beans and spring barley) and 180 cm (sugar beet). A boron trifluoride detector was used to measure the density of the slow-neutron cloud, produced when fast-neutrons from a 50 mCi Am/Be source (Van Bavel and Stirk, 1967) collide with hydrogen nuclei of the soil water. The detector has a range of between 10 cm and 20 cm from the fast-neutron source (Visualingham and Tandy, 1972). An Algol 68 computer programme was used to convert the slow-neutron count rate to volumetric water content using calibration constants calculated in the laboratory (McGowan and Williams, 1980). The output included the percentage soil water content at each depth, summed from the surface. A full account of the errors associated with the neutron probe technique is given by McGowan and Williams (1980).

7.2.2 Tensiometer Data

The soil water tension to 0.08 MPa was measured with tensiometers in 1983. These instruments were installed, using a 1 cm diameter hand-auger, in three replicates of each treatment at depths of 20, 40, 60, 80 and 100 cm (field beans, spring barley, grass) and 20, 40, 60, 80, 120 and 140 cm (sugar beet).

The tensiometers were constructed in the laboratory to Webster's (1966) design. A ceramic porous cup (Soil Moisture Equipment Corporation), bonded to Portex nylon tubing was connected to a mercury

reservoir via a water-filled nylon capillary tube. Field readings, taken every two days, were converted from a mercury manometer reading (cm mercury) to hydraulic potential (MPa) relative to the soil surface with corrections for the height of the mercury cup and the mercury/water interfacial tension.

7.2.3 Thermocouple Psychrometer Data

Soil water potentials lower than -0.08 MPa were measured with thermocouple psychrometers (Wescor PT-51). The water potential is the sum of the matric potential and the osmotic potential. However the osmotic potential was found to be negligible in these soils (Gregory, McGowan and Biscoe, 1978).

The psychrometers were installed in two replicates of each treatment at 20, 40 and 60 cm depth (field beans, spring barley, grass) in 1983 and in three replicates of each treatment at 20, 40, 60 and 80 cm depth (field beans, spring barley and sugar beet) in 1984.

A hole was dug, using a 10 cm diameter auger, 1 m from the edge of the plot and close to the access tube. The soil from each 10 cm increment was sealed in a polythene bag to prevent moisture loss while the porous ceramic cup was inserted horizontally into the side of the hole at the required depth. The soil was then replaced. To allow for equilibration, the first readings (recorded with a Wescor MJ55 microvoltmeter) were not taken until two weeks after installation.

The thermocouple psychrometer provides an output which is proportional to the soil vapour pressure (equation 7.1).

$$w = \frac{RT}{V_m} \ln {}^{e}/_{e_o} \qquad 7.1$$

where:

w = Water potential (Pa)

R = Universal gas constant

T = Temperature (°K)

V_m = Molar volume of water (m^3)

${}^{e}/_{e_o}$ = Relative humidity of the soil

A 5 mA current, passed for 15 seconds, cooled the thermocouple junction and condensed a droplet of water upon it. Evaporation of the droplet caused a temperature difference, proportional to the vapour pressure of the air, between the wet and dry junctions. This temperature difference was recorded by the microvoltmeter, corrected to 20°C by using equation 7.2 and converted to water potential by using the manufacturer's calibration.

$$R_{20} = \frac{R}{0.376 + 0.0312T} \qquad 7.2$$

Gregory, McGowan and Biscoe (1978)

where:

R_{20} = Output corrected to 20°C

R = Output reading (μV)

T = Initial reading for soil temperature (mV)

7.3 Results and Discusssion

The errors associated with the measurement of soil water are usually large due to variations in soil type across a trial site. McGowan and Williams (1980) reported a variation of +/- 5% in water content at each

depth. They also observed that the equivalent amount of water stored at depths in replicated profiles frequently differed by +/- 50 mm. It was not possible to monitor a sufficiently large number of replicates to eliminate the high variability of the data. Consequently the treatment differences were generally not found to be significant but certain trends developed which suggested how soil compaction influenced crop water use.

7.3.1 Extraction Depths in 1983 and 1984

The time at which roots begin to extract appreciable quantities of water from a specific depth within the soil profile can be inferred from discontinuities in the graphs of the water content against time for each depth monitored. From such curves it is possible to follow the progress of the drying front, sometimes referred to as the 'effective rooting depth' (McGowan, 1974), down the profile. The water content for each discontinuity is a measure of the 'dynamic field capacity' for that depth and crop, i.e. it represents the moisture content when extraction commences at that depth. Any reduction in water content below the dynamic field capacity value is attributable to the root extraction of water or upward flux of water through the profile due to evaporation by soil and vegetation (McGowan, 1974). Wind (1955) found that water may enter an upper horizon from below if the soil in the lower level is at a higher potential. However, this is only of major importance when the water table is within 1 m of the soil surface. Any loss of water in excess of the dynamic field capacity may be attributed, with minor errors, to drainage. The soil moisture deficit for the whole profile may then be calculated from the sum of the deficit for each horizon within the extraction depth. The evaporation (here defined as the sum of direct soil water loss plus crop transpiration) may be taken as the total soil moisture deficit plus rain.

Following a wet spring in 1983, soil drying did not occur in field bean or spring barley until the beginning of June (89 days after sowing), and in the case of sugar beet, until the beginning of July (55 days after sowing).

Drying was easily detectable since the rewetting of the soil profile as the result of precipitation was infrequent, until September. The effective rooting depths for crops grown in 1983 are shown in Figure 7.1. The rate of penetration of the drying front down the profile was generally reduced by soil compaction while the maximum effective rooting depth was consistently less for compacted crops, especially sugar beet, although none of the differences were significant. The development of the drying front down the profile under grass appears to have been checked between 100 and 110 days after sowing. This may have been attributable to the silage cut, taken 100 days after sowing from which the crop did not recover. The final extraction depth may also have been reduced by the cut; an observation reported by Goode (1956). Garwood and Sinclair (1979) observed that perennial ryegrass extracted water from a soil depth of up to 80 cm; at least 10 cm deeper than the 1983 grass crop.

In 1984 constant rewetting of the soil made the interpretation of the data difficult and rain in June (35 mm in one event) prevented detection of soil drying until 90 days after sowing the field bean and spring barley crops, and 73 days after sowing the sugar beet. Figure 7.2 shows the effective rooting depths for crops grown in 1984. There was a significant reduction in the development of the drying front down the profile and in the maximum effective rooting depth of field beans ($p<0.05$) and sugar beet ($p<0.001$) after soil compaction but spring barley was unaffected. The rapid descent of the drying front in barley, in excess of the 1-2 cm per day, expected from an expanding root system (McGowan and Williams,

Figure 7.1 The effective rooting depth of field bean (A), spring barley (B) and sugar beet (C) and grass (D) as influenced by soil compaction in 1983
Control (o); Compact (●)

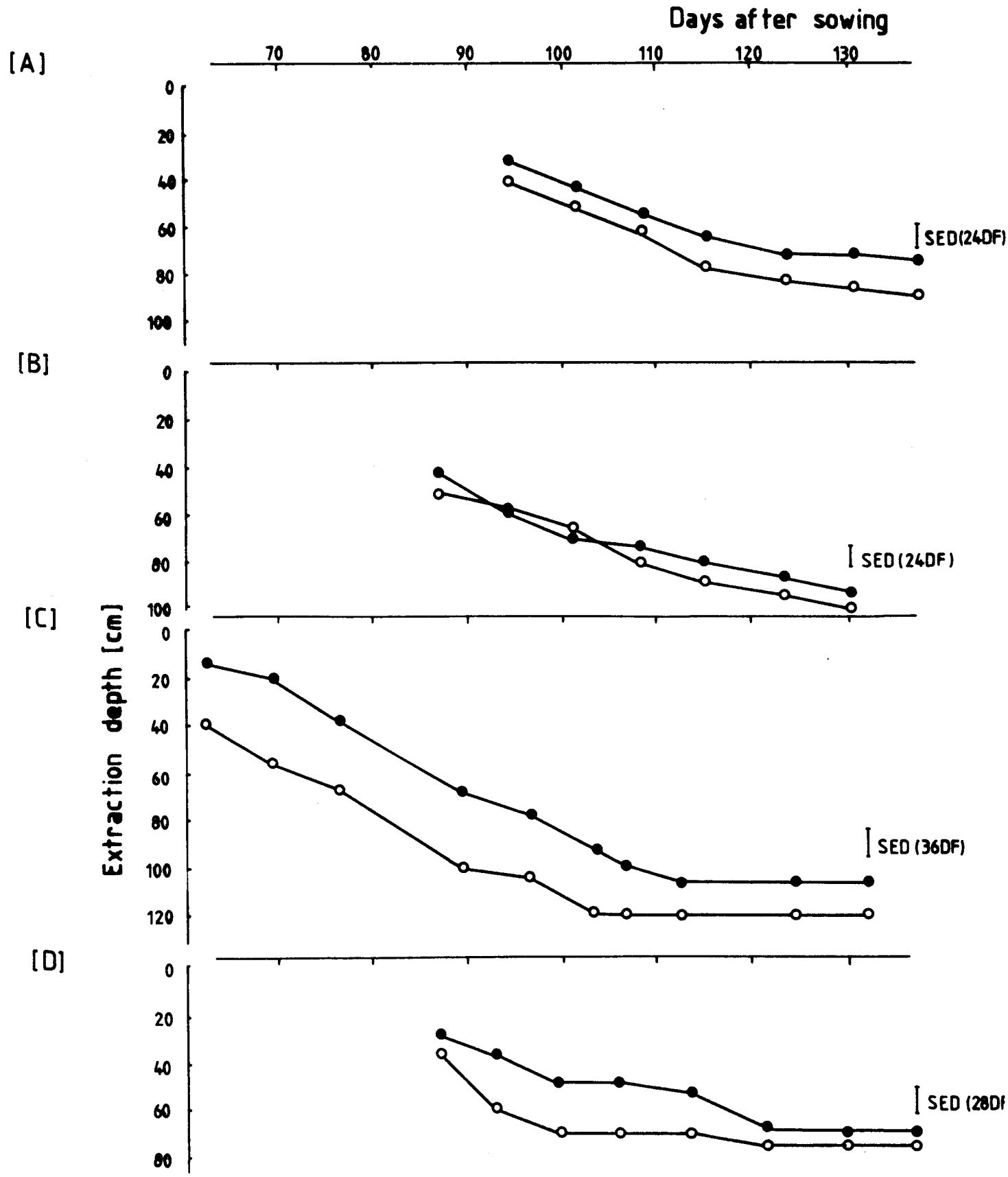
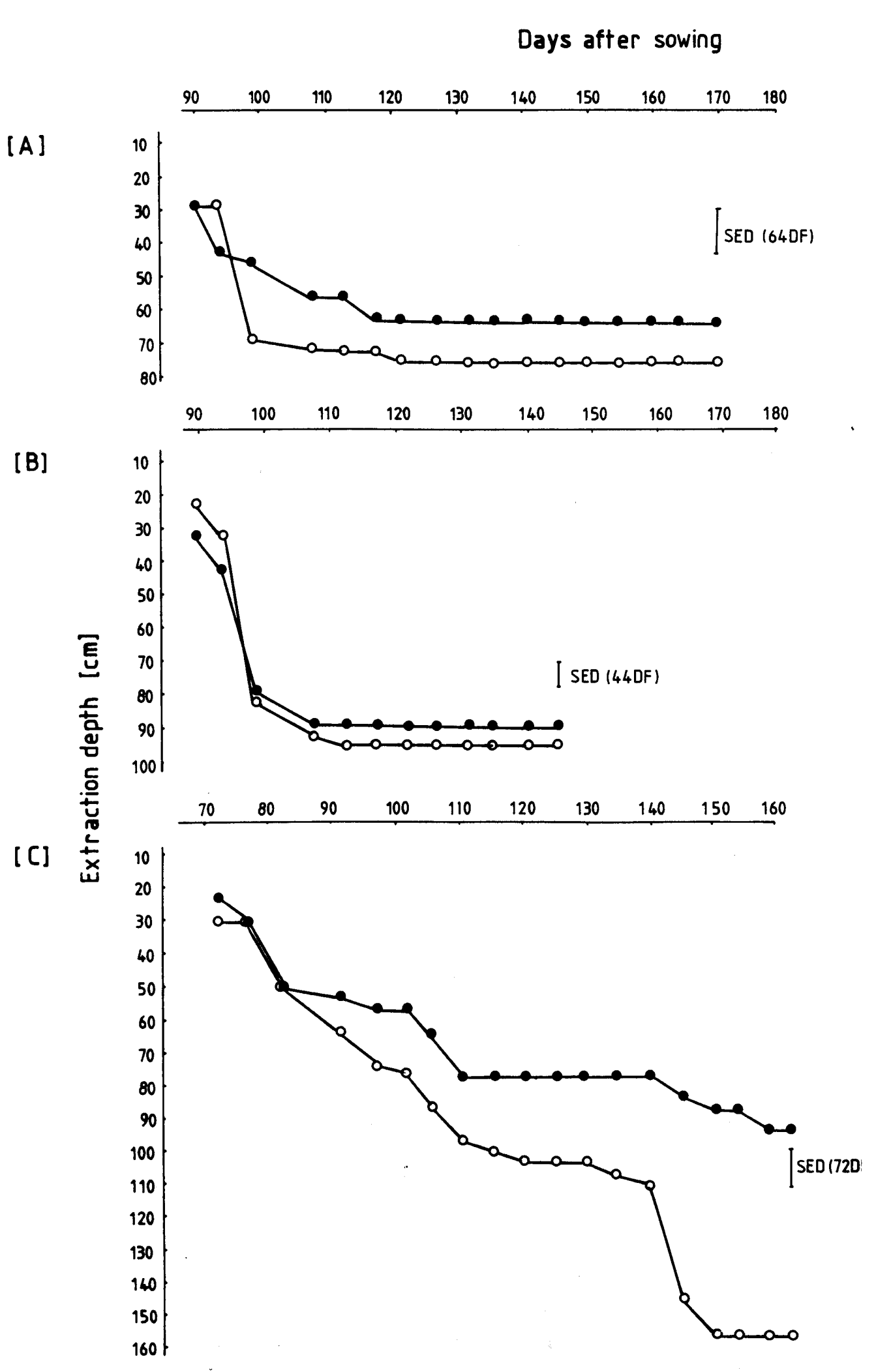

Days after sowing
70
80
90
100
110
120
130
[A]
[B]
[C]
[D]
Extraction depth [cm]
0
20
40
60
80
100
120
SED(24DF)
SED (24DF)
SED (36DF)
SED (28DF

Figure 7.2 The effective rooting depth of field bean (A), spring barley (B) and sugar beet (C) as influenced by soil compaction in 1984. Control (o); Compact (●)


Days after sowing
[A]
[B]
[C]
Extraction depth [cm]
SED (64DF)
SED (44DF)
SED (72D)

1980), is probably the result of soil drying by an established root system following a period of rain. The relationship between actual rooting depth, calculated from washed core samples (Chapter 6), and the effective rooting depth is shown in Figure 7.3 for 1984 crops. In agreement with McGowan (1974) and Durrant, Love and Draycott (1973), some barley roots penetrated 10 cm deeper than the effective rooting depth. The actual rooting of field bean and sugar beet did not correlate as well with the calculated extraction depth especially early in the season.

7.3.2 Cumulative Deficits in 1983 and 1984

The cumulative soil moisture deficits for 1983 are shown in Figure 7.4. Compaction generally reduced the soil moisture deficits in the crops studied, apart from barley, but the differences were not significant.

A minimal difference between treatments occurred in the water deficit of field beans, 101 days after sowing. This difference increased slightly, reaching a maximum of only 9 mm at harvest. Spring barley showed no overall change in water deficit attributable to compaction but the data and visual inspection suggested that an increasing water deficit of the compact treatment, relative to the control, 133 days after sowing, may possibly have been due to a delay in the senescence of that treatment.

The sugar beet established a difference of 30 mm of moisture deficit, between treatments, by 90 days after sowing which was generally maintained throughout the season. Part of this large difference may have been due to a population reduction of 35% in the compacted treatment (Chapter 2). The compact grass crop generally maintained a reduction of 18 mm throughout the season, compared to the control. It is interesting to note that although only limited regrowth of grass followed the sward cut

Figure 7.3 The relationship between the actual rooting depth and the effective rooting depth of field beans (2), spring barley (1) and sugar beet (3) in 1984. Control (o); Compact (●)

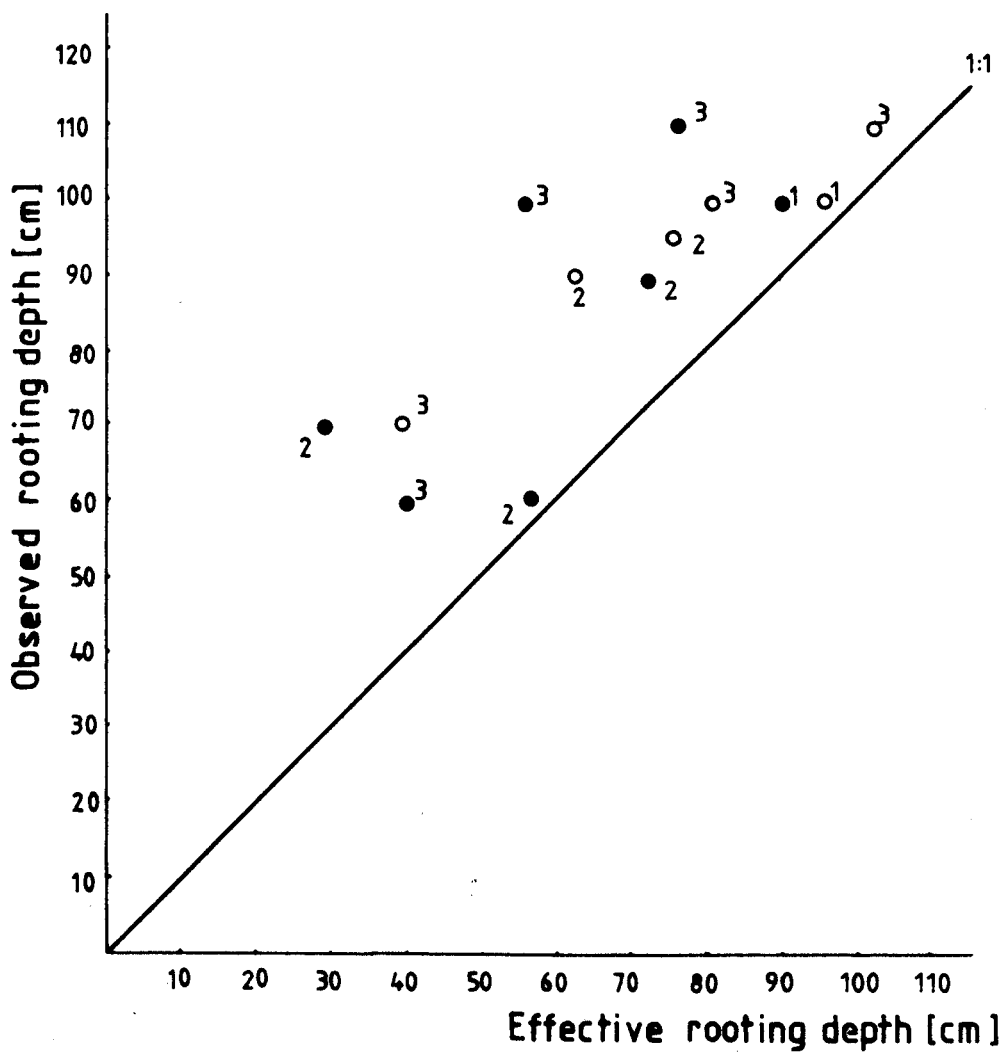
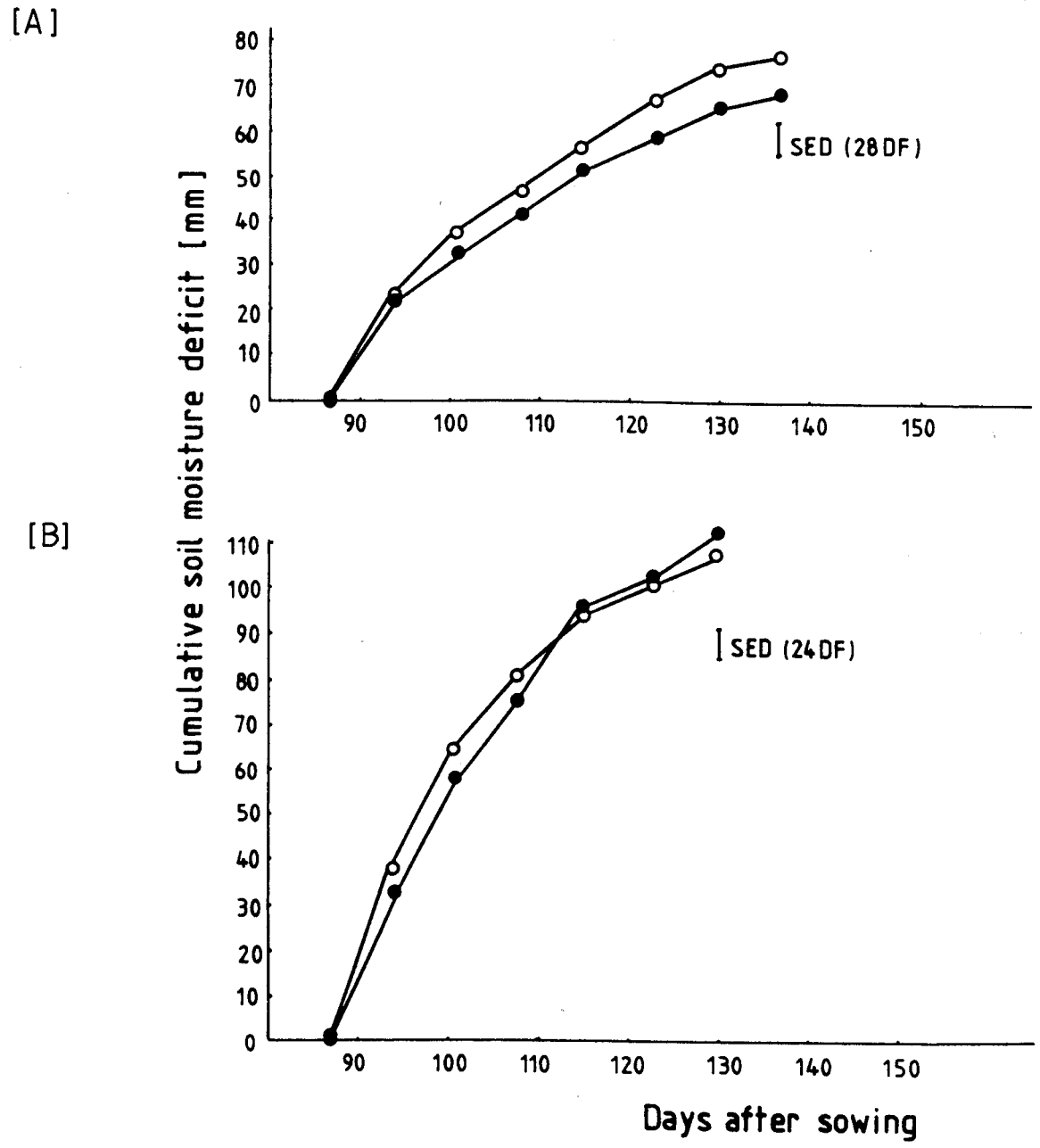
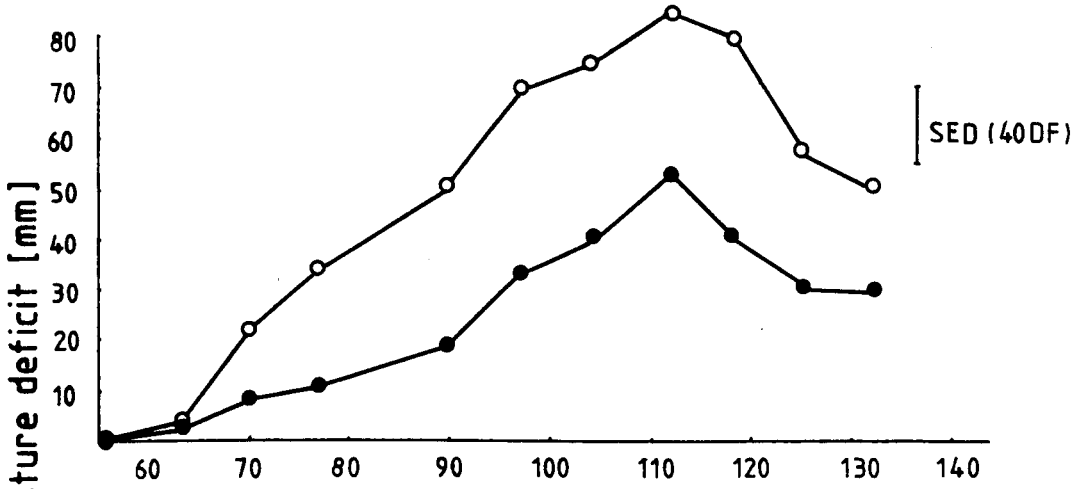

Observed rooting depth [cm]
Effective rooting depth [cm]
1:1
120
110
100
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
70
80
90
100
110

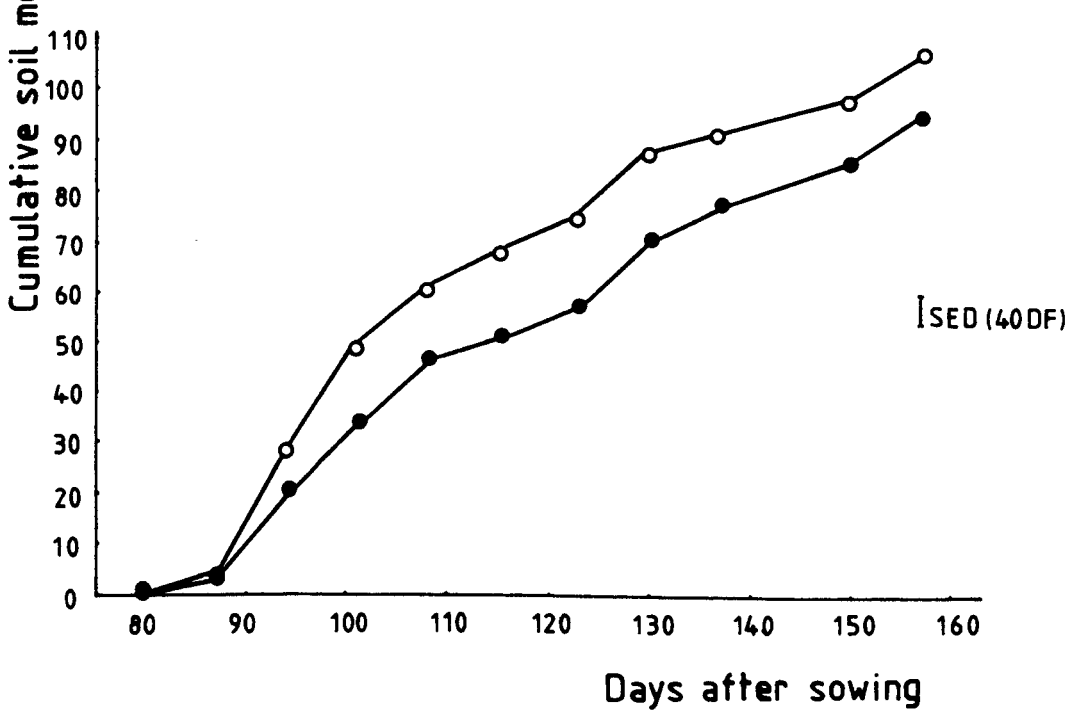
Figure 7.4 The influence of soil compaction on the cumulative soil moisture deficit of field beans (A), spring barley (B), sugar beet (C) and grass (D) in 1983. Control (o); Compact (●)


[A]
[B]
Cumulative soil moisture deficit [mm]
0
10
20
30
40
50
60
70
80
90
100
110
90
100
110
120
130
140
150
SED (28 DF)
SED (24 DF)
Days after sowing

[C]


80
70
60
50
40
30
20
10
60
70
80
90
100
110
120
130
140
SED (40DF)

[D]


Cumulative soil moisture deficit [mm]
110
100
90
80
70
60
50
40
30
20
10
0
80
90
100
110
120
130
140
150
160
SED (40DF)
Days after sowing

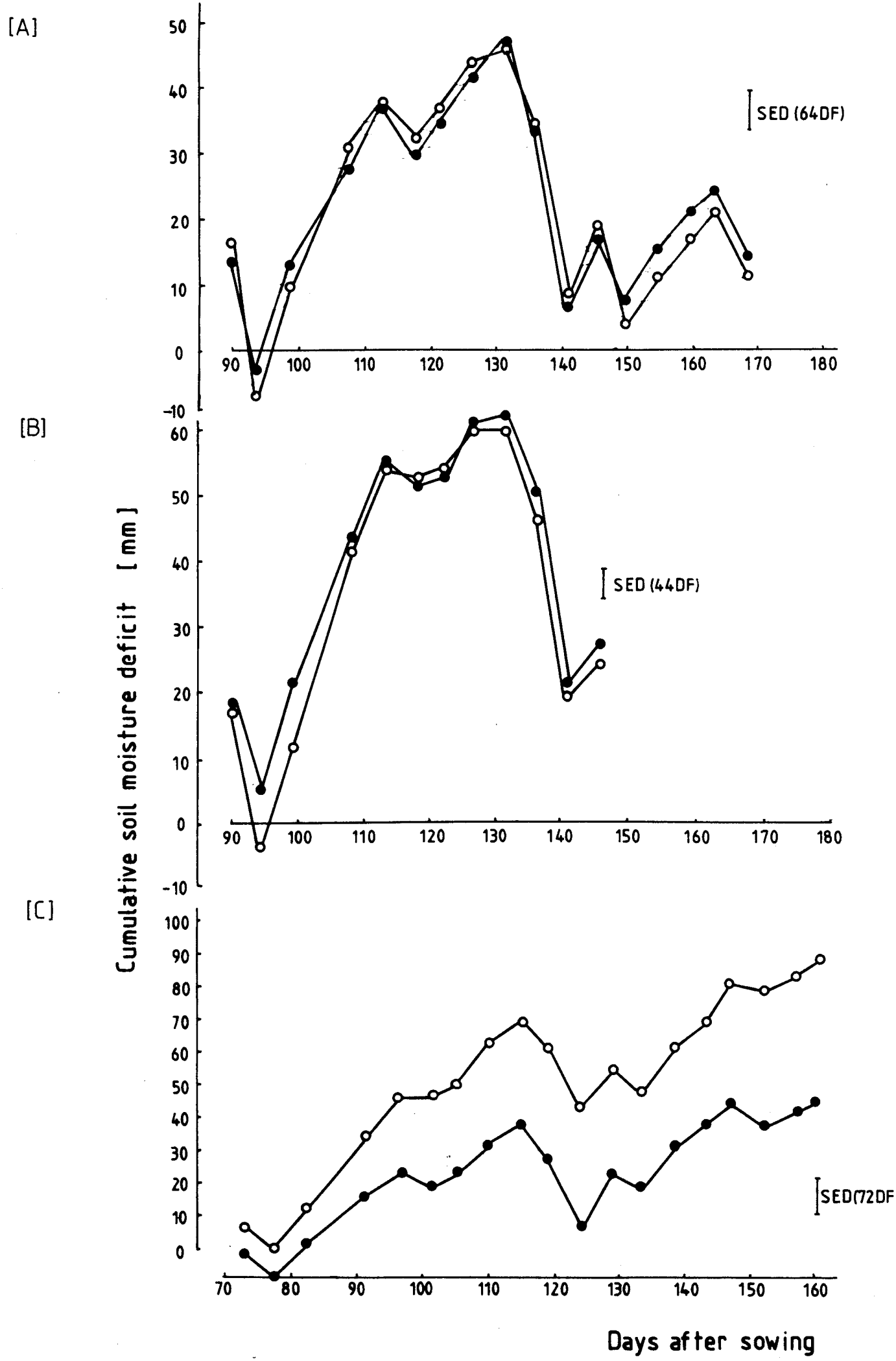
100 days after sowing, the cumulative deficit continued to increase after this date. The effect of defoliation on water use of the grass crop was investigated by Johns and Lazenby (1973). They found that for an irrigated crop, the sensitivity of water use to defoliation was inversely proportional to the leaf area index. However, if soil water reserves were low, it was the availability of soil water, rather than the intercepted solar radiation energy, which had most effect on water use. Therefore, it was possible to speculate that because soil water reserves were already low, the sward cut did not reduce the cumulative water use.

In 1984 (Figure 7.5) the soil moisture deficit of field beans and spring barley was unchanged by soil compaction despite large reductions in plant population of 41% and 50% respectively. This may have been a result of compensation for a low plant population by the compact crop which developed an extensive root system and therefore extracted similar amounts of water to the control (Chapter 6).

However, compaction reduced the cumulative water deficit of sugar beet throughout the season ($p<0.001$) and resulted in a difference of 44 mm at harvest. Part of this large reduction may have been due to a population reduction of 64% in the compact treatment. It is possible that the sugar beet population may have been reduced by compaction to such an extent that any compensatory root growth was insufficient to prevent a decrease in crop water use.

The maximum soil moisture deficits achieved were greater in 1983 for spring barley and field beans. However the sugar beet control plot produced a 14 mm greater deficit in 1984 than in 1983. The compact sugar beet treatment deficit was similar in both years.

Figure 7.5 The influence of soil compaction on the cumulative soil moisture deficit of field beans (A), spring barley (B) and sugar beet (C) in 1984.
Control (o); Compact (●)


[A]
[B]
[C]
Cumulative soil moisture deficit [mm]
SED (64DF)
SED (44DF)
SED(72DF
Days after sowing

7.3.3 Soil Water Deficits in Individual Horizons in 1983 and 1984

The distribution of the deficits in 30 cm increments of the soil profile was examined using a procedure described by Gregory (1976) and the pattern was found to be similar in 1983 and 1984. Figure 7.6(c) shows the distribution of water deficit at individual levels for sugar beet, the only crop which displayed treatment differences, in 1984. Drying increased rapidly in the lower levels as the deficit in the level above approached its maximum. Rewetting, 115 days after sowing, did not penetrate below 30 cm. At each horizon, compaction delayed the soils drying and reduced the maximum moisture deficit. Therefore compaction reduced the water uptake of the sugar beet crop in each horizon.

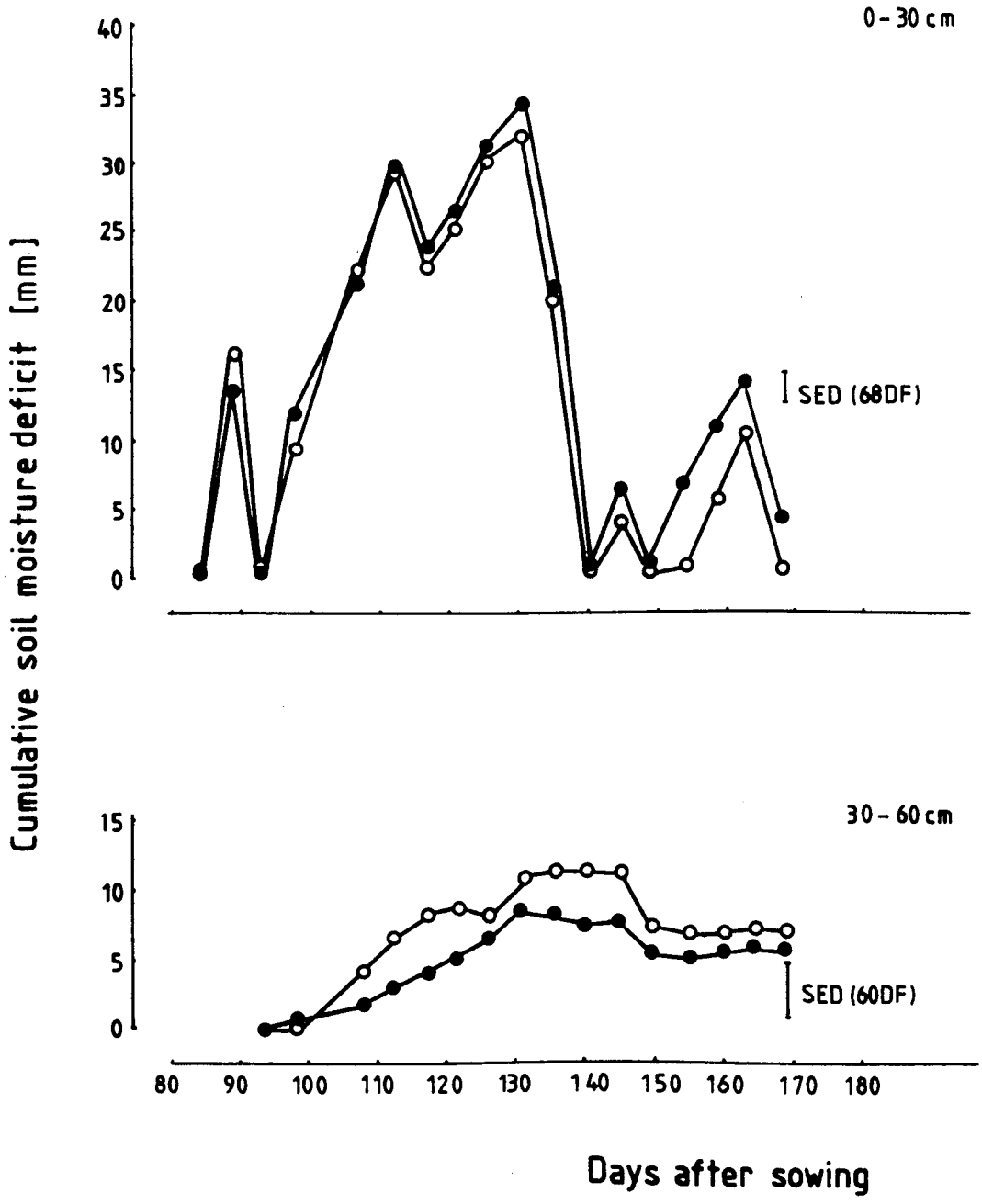
Compaction did not reduce the distribution of deficits down the profile in field beans (Figure 7.6(a)) or in spring barley (Figure 7.6(b)) in any horizon in 1984.

7.3.4 Soil Water Tension in 1983 as Measured by Tensiometer

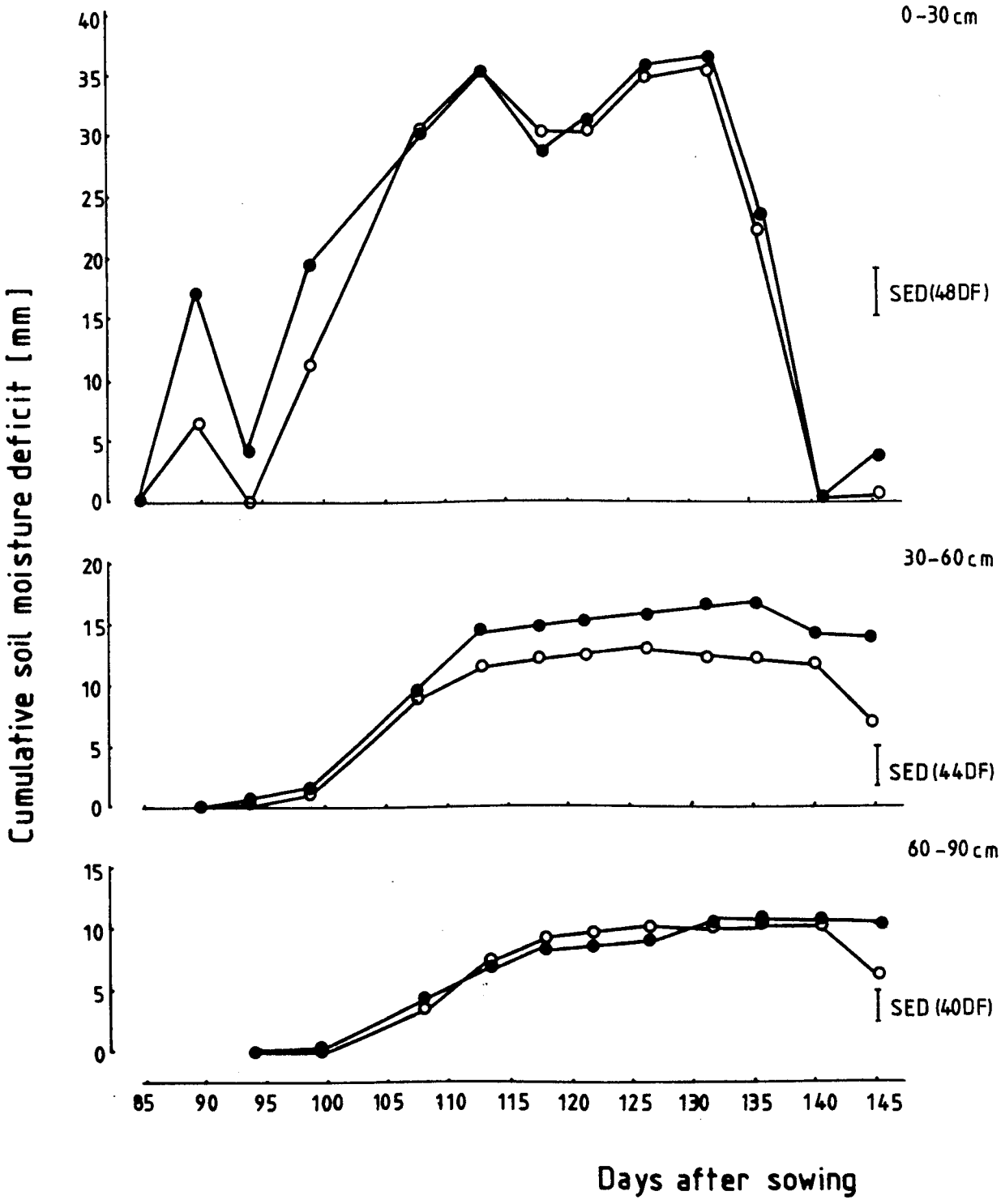
The ease with which roots extract water from a soil decreases as the soil dries and water from the deeper, wetter horizons is then used by the growing crop. The rate of soil drying can be monitored by tensiometers placed at increasing depths in the profile and the date on which water extraction begins can be inferred by the marked change in soil water tension at that depth. Tensiometers are more sensitive than the neutron probe to the onset of drying. However they can only detect changes in soil water tension to 0.08 MPa. As tensions rise above 0.08 MPa the tensiometers fail due to cavitation within the water columns. Thermocouple psychrometers may then be used to measure lower water potentials.

Figure 7.6 The influence of soil compaction on the distribution of water deficit in 30 cm increments of soil profile in 1984 under field beans (A), spring barley (B) and sugar beet (C). Control (o); Compact (●)

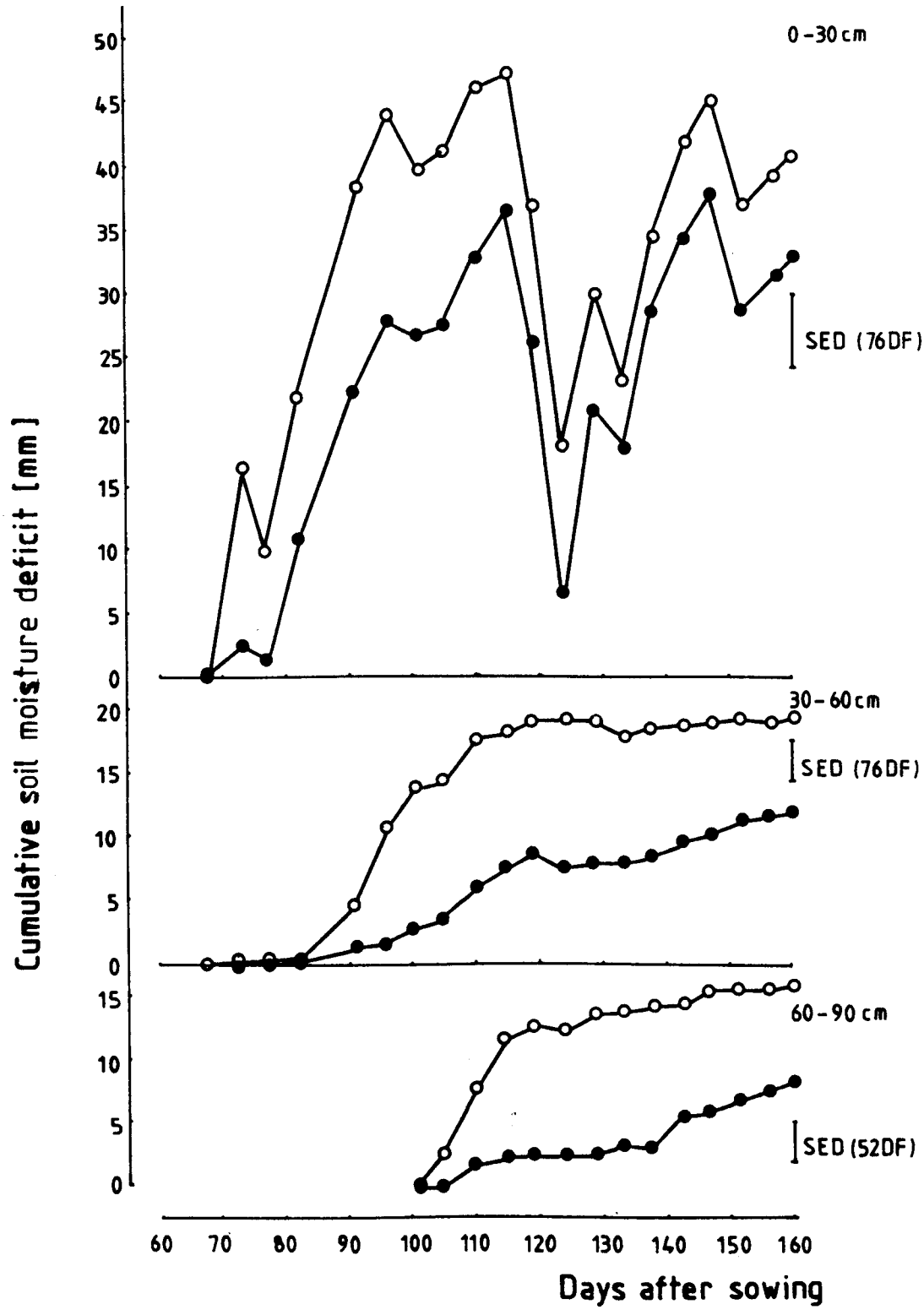
[A]


0 - 30 cm
40
35
30
25
20
15
10
5
0
SED (68DF)
30 - 60 cm
15
10
5
0
SED (60DF)
80
90
100
110
120
130
140
150
160
170
180
Cumulative soil moisture deficit [mm]
Days after sowing

[B]


0-30 cm
30-60 cm
60-90 cm
SED(48DF)
SED(44DF)
SED(40DF)
Cumulative soil moisture deficit [mm]
Days after sowing
0
5
10
15
20
25
30
35
40
85
90
95
100
105
110
115
120
125
130
135
140
145

[C]


0-30 cm
SED (76DF)
30-60 cm
SED (76DF)
60-90 cm
SED (52DF)
Cumulative soil moisture deficit (mm)
Days after sowing
0
5
10
15
20
25
30
35
40
45
50
60
70
80
90
100
110
120
130
140
150
160

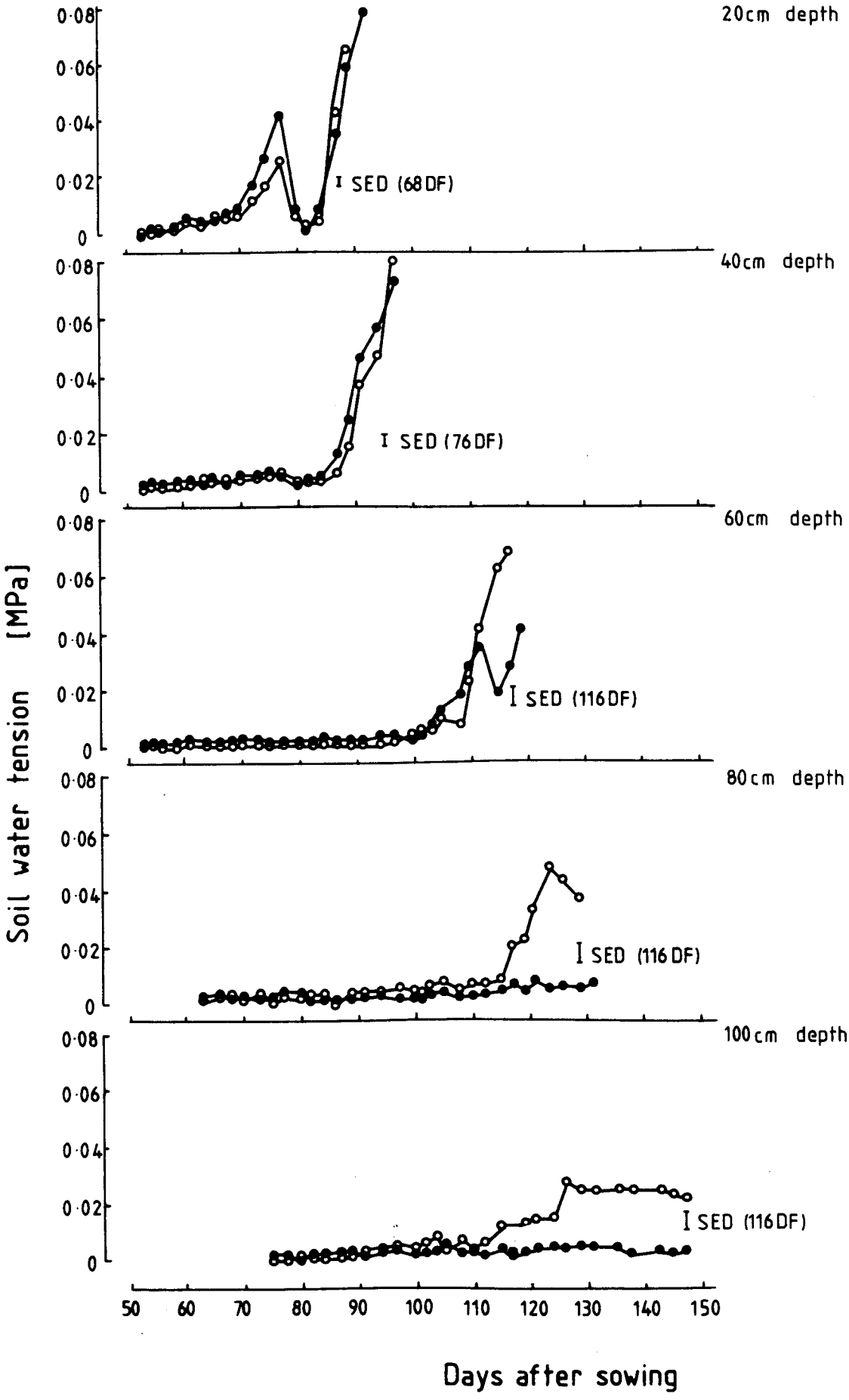
The change in the water tension throughout the 1983 season is shown in Figure 7.7 for field beans, spring barley, sugar beet and grass. Compaction generally delayed the date on which water extraction was observed at a specific depth in all crops but it was not found to reduce the maximum depth of extraction. This does not agree with neutron probe data in which differences in maximum extraction depth were observed in all crops. Unfortunately comprehensive root length measurements were not made throughout the 1983 season. In the soil type studied, very small differences in water content can relate to large differences in matric potential (see moisture release curve, Figure 3.1) and the neutron probe has been shown to have a precision of +/- 3 mm in the measurement of changes in water storage in a 1 m soil profile (McGowan and Williams, 1980). Therefore it is probable that tensiometers can detect the presence of a small number of roots of compacted crops which reach the same maximum extraction depth as the controls.

In 1984 there was generally no difference in the maximum depth of rooting, as assessed from washed soil cores, however there was a large difference in the length of root removed from the deeper layer in every crop (Chapter 6). The rate of descent of the drying front was also in advance of that calculated from neutron probe data, probably for the reason discussed above.

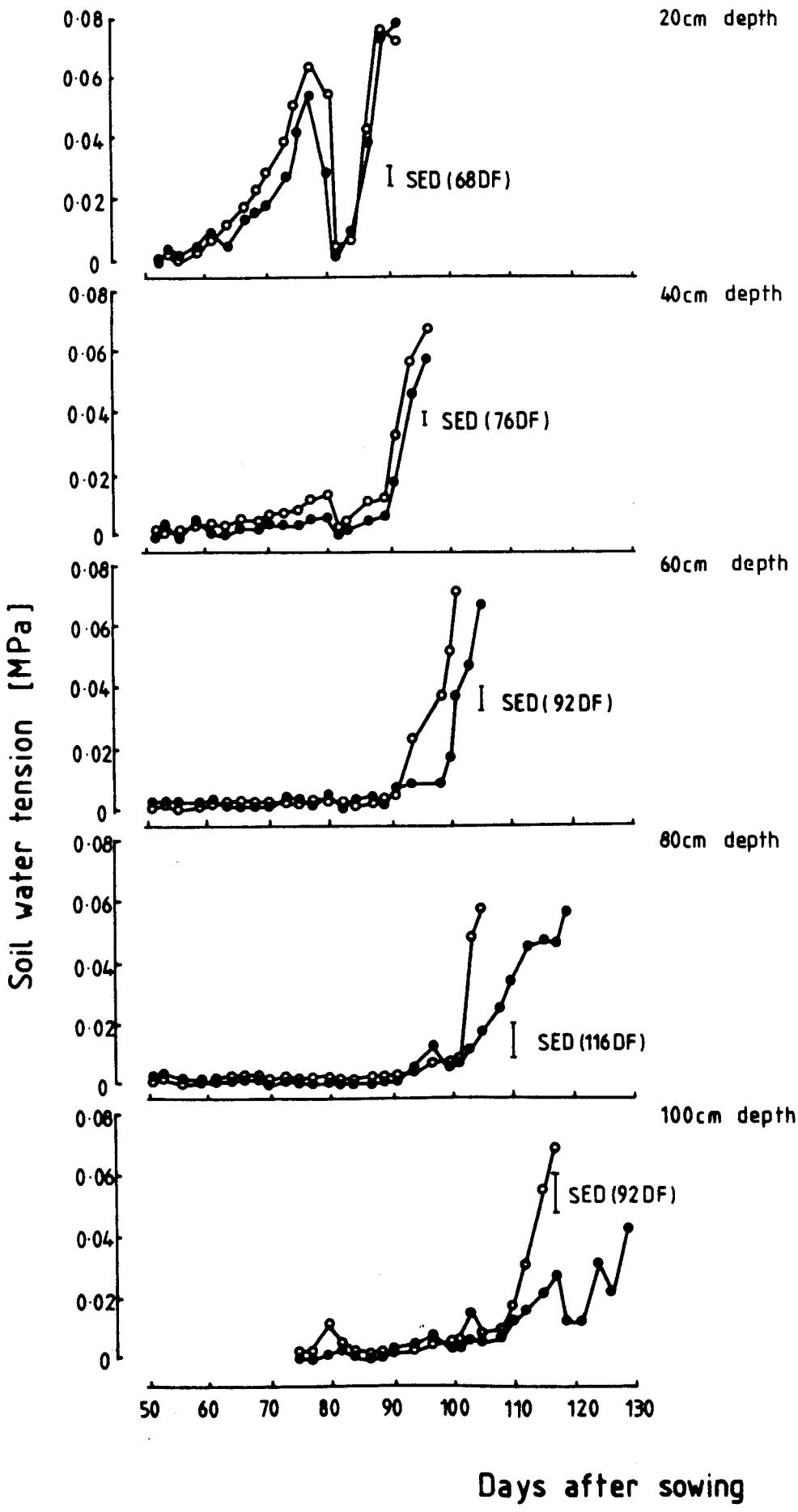
The tensiometer data for 1983 suggested that the field bean 'drying front' extended down the profile at a similar rate to that of spring barley (maximum drying depth: 100 cm) but it only achieved a maximum depth of 80 cm. Sugar beet extracted water earlier and to a greater depth in the profile than the other crops (Figure 7.8). This may have been a result of higher air temperatures during the early development phase of the

Figure 7.7 The effect of soil compaction on the soil water tension in 1983 at depths under field beans (A), spring barley (B), sugar beet (C) and grass (D). Control (o); Compact (●)

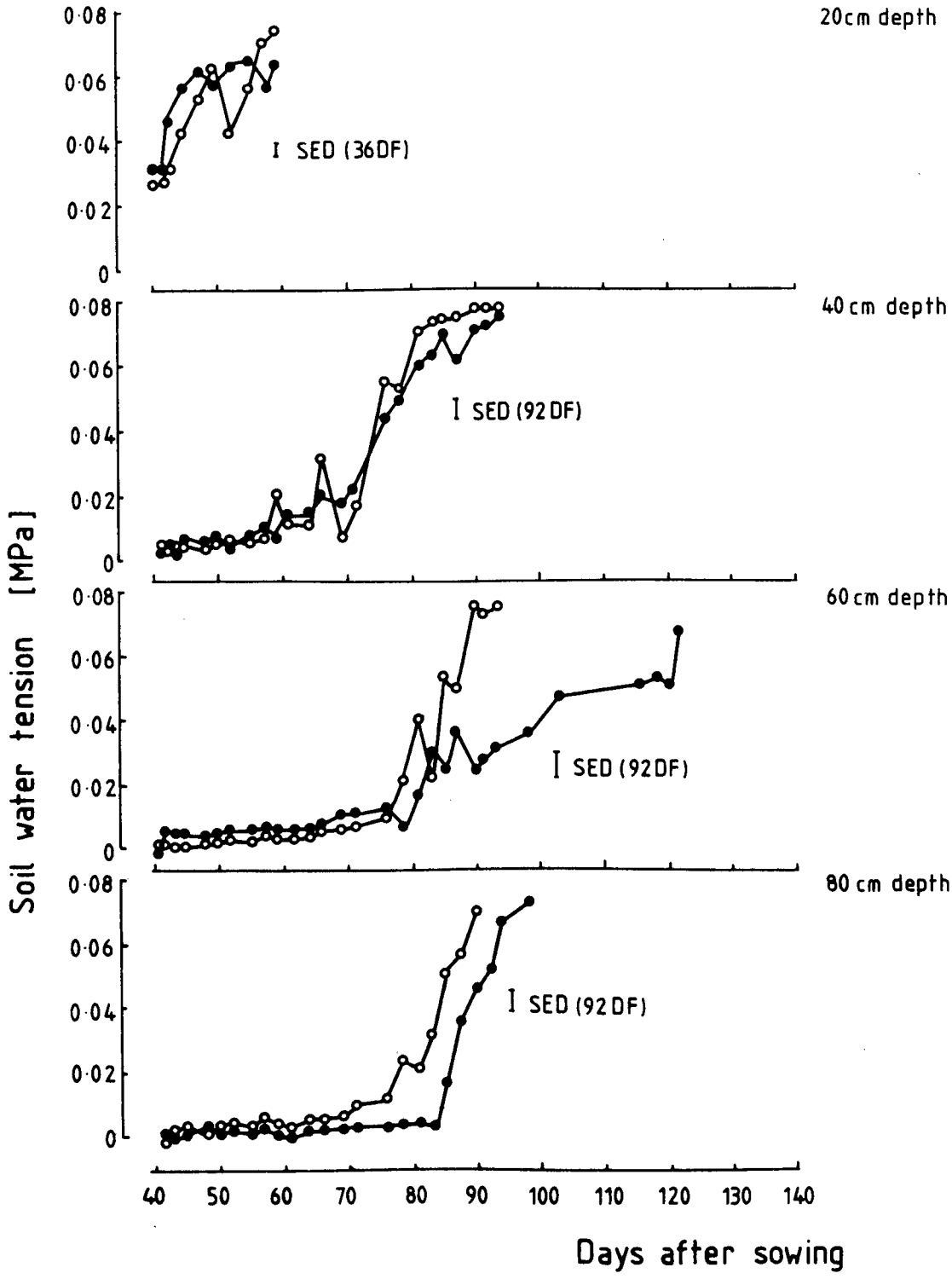
[A]


20cm depth
40cm depth
60cm depth
80cm depth
100cm depth
I SED (68DF)
I SED (76DF)
I SED (116DF)
I SED (116DF)
I SED (116DF)
0·08
0·06
0·04
0·02
0
50
60
70
80
90
100
110
120
130
140
150
Soil water tension [MPa]
Days after sowing

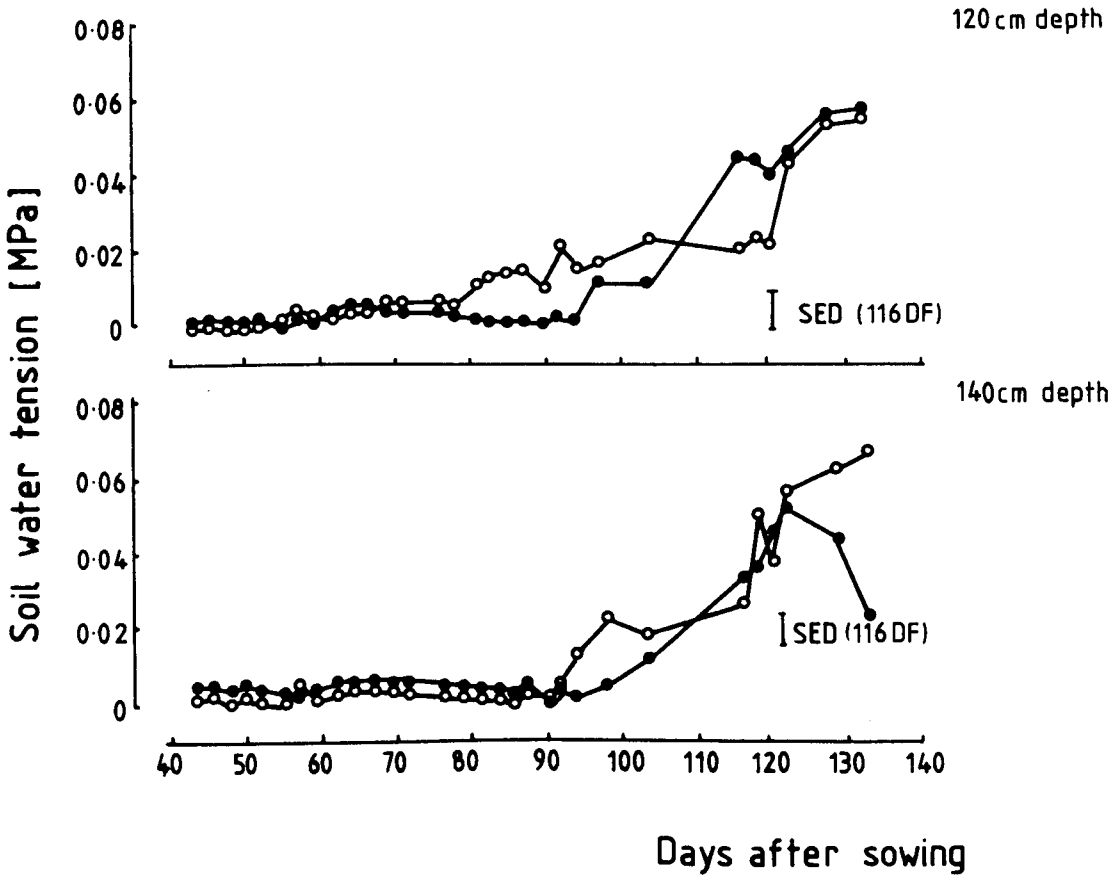
[B]


20cm depth
40cm depth
60cm depth
80cm depth
100cm depth
SED (68DF)
SED (76DF)
SED (92DF)
SED (116DF)
SED (92DF)
0·08
0·06
0·04
0·02
0
Soil water tension [MPa]
50
60
70
80
90
100
110
120
130
Days after sowing

[C]


20cm depth
40cm depth
60cm depth
80 cm depth
SED (36DF)
SED (92DF)
SED (92DF)
SED (92DF)
0·08
0·06
0·04
0·02
0
Soil water tension [MPa]
40
50
60
70
80
90
100
110
120
130
140
Days after sowing

[C]


120 cm depth
140 cm depth
Soil water tension [MPa]
0·08
0·06
0·04
0·02
0
SED (116 DF)
40
50
60
70
80
90
100
110
120
130
140
Days after sowing

[D]

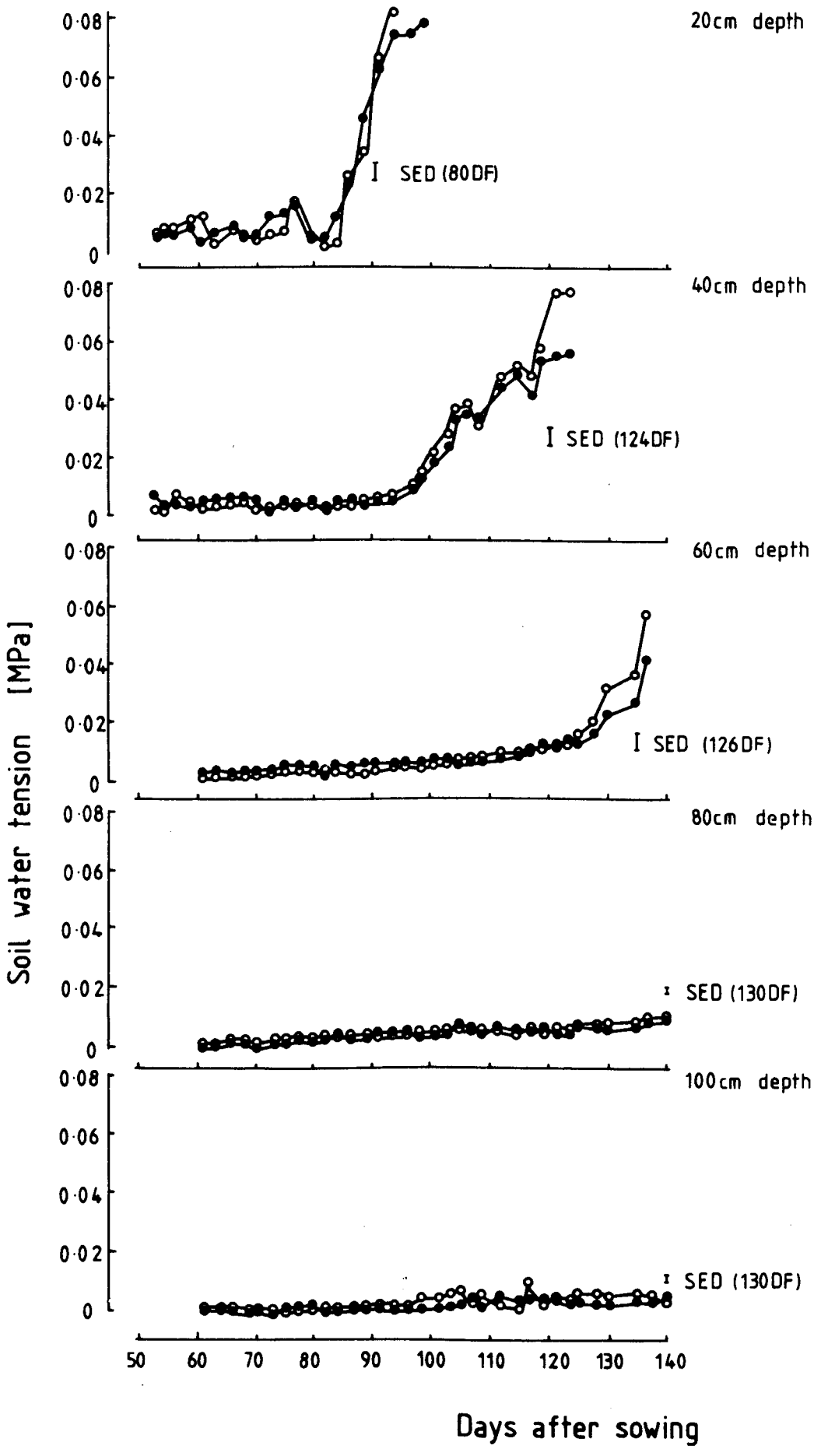
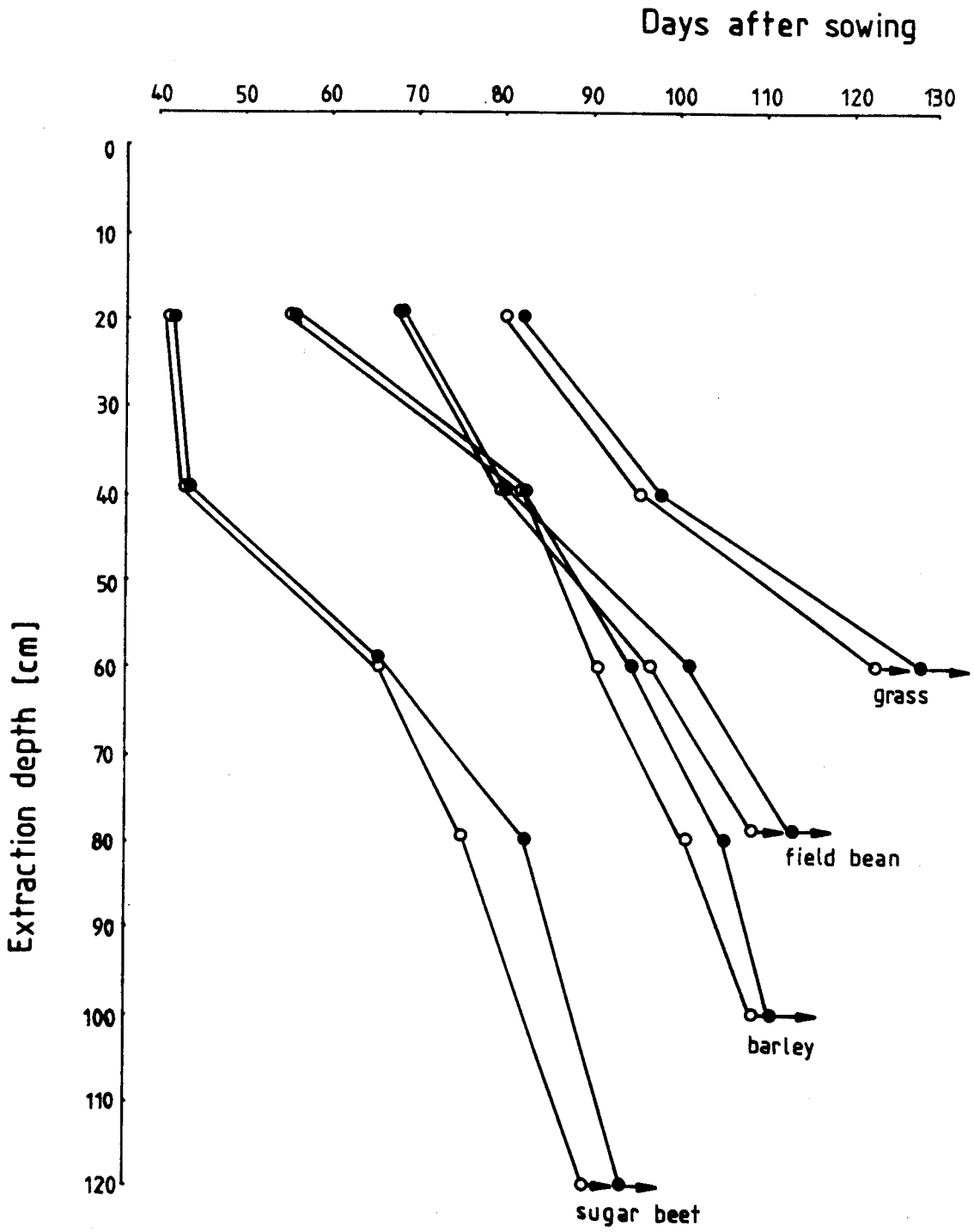

20cm depth
40cm depth
60cm depth
80cm depth
100cm depth
SED (80DF)
SED (124DF)
SED (126DF)
SED (130DF)
SED (130DF)
0·08
0·06
0·04
0·02
0
Soil water tension [MPa]
50
60
70
80
90
100
110
120
130
140
Days after sowing

Figure 7.8 The influence of soil compaction on the movement of the 'drying front' down the profile, as measured by tensiometers under field beans, spring barley, sugar beet and grass. Control (o); Compact (●)


Days after sowing
40
50
60
70
80
90
100
110
120
130
0
10
20
30
40
50
60
70
80
90
100
110
120
Extraction depth [cm]
grass
field bean
barley
sugar beet

sugar beet crop and a period of low rainfall directly after emergence of the sugar beet (sown 60 days after the other crops) which possibly also stimulated deeper rooting. Weaver and Himmel (1930) found that rooting depth increased with decreasing water content, until the soil became too dry for root growth. Grass extracted water later and to a markedly reduced depth than the other crops.

The rate of drying, as inferred from the change in water tension with time, although delayed, was only significantly reduced by compaction in barley at 100 cm (0.0065 MPa/day (control); 0.0015 MPa/day (compact); $p<0.05$) and in field beans at 80 cm (0.0046 MPa/day (control); 0.0004 MPa/day (compact); $p<0.01$). This may have been because either there were fewer roots at depth in the compact treatment, or the roots were not as efficient at extracting water from the profile.

7.3.5 Soil Water Potential as Measured with Soil Psychrometers in 1983 and 1984

The water extraction of sugar beet was not monitored by soil psychrometers in 1983. The minimum recorded soil water potentials (Table 7.1) were consistently higher at all measured depths and for all crops monitored, in the compact treatment. This inferred that compaction had limited the extent of profile drying. However these effects of soil compaction were small compared to the marked differences between crops. Grass developed the lowest water potential in the surface horizon but like field beans caused only limited drying at 60 cm depth, even in non-compacted soil. Spring barley by contrast, developed uniformly low potentials throughout the profile. (Seasonal water potentials for grass, spring barley and field beans are given in Appendix 6).

Table 7.1 Minimum recorded soil water potentials (MPa) in 1983

Depth (cm)	Soil water potential (MPa)					
	field beans		grass		spring barley	
	control	compact	control	compact	control	compact
20	-1.56±0.05	-1.36±0.22	-2.81±0.15	-2.25±0.08	-2.19±0.07	-1.94±0.17
40	-1.15±0.11	-1.03±0.06	-1.78±0.01	-1.16±0.16	-2.03±0.09	-1.51±0.23
60	-0.48±0.32	-0.35±0.28	-0.67±0.46	-0.14±0.03	-1.73±0.35	-1.12±0.46

± Standard Error

(It was not possible to use S.E.D. for comparison between means because minimum recorded soil water potentials did not necessarily occur on the same date)

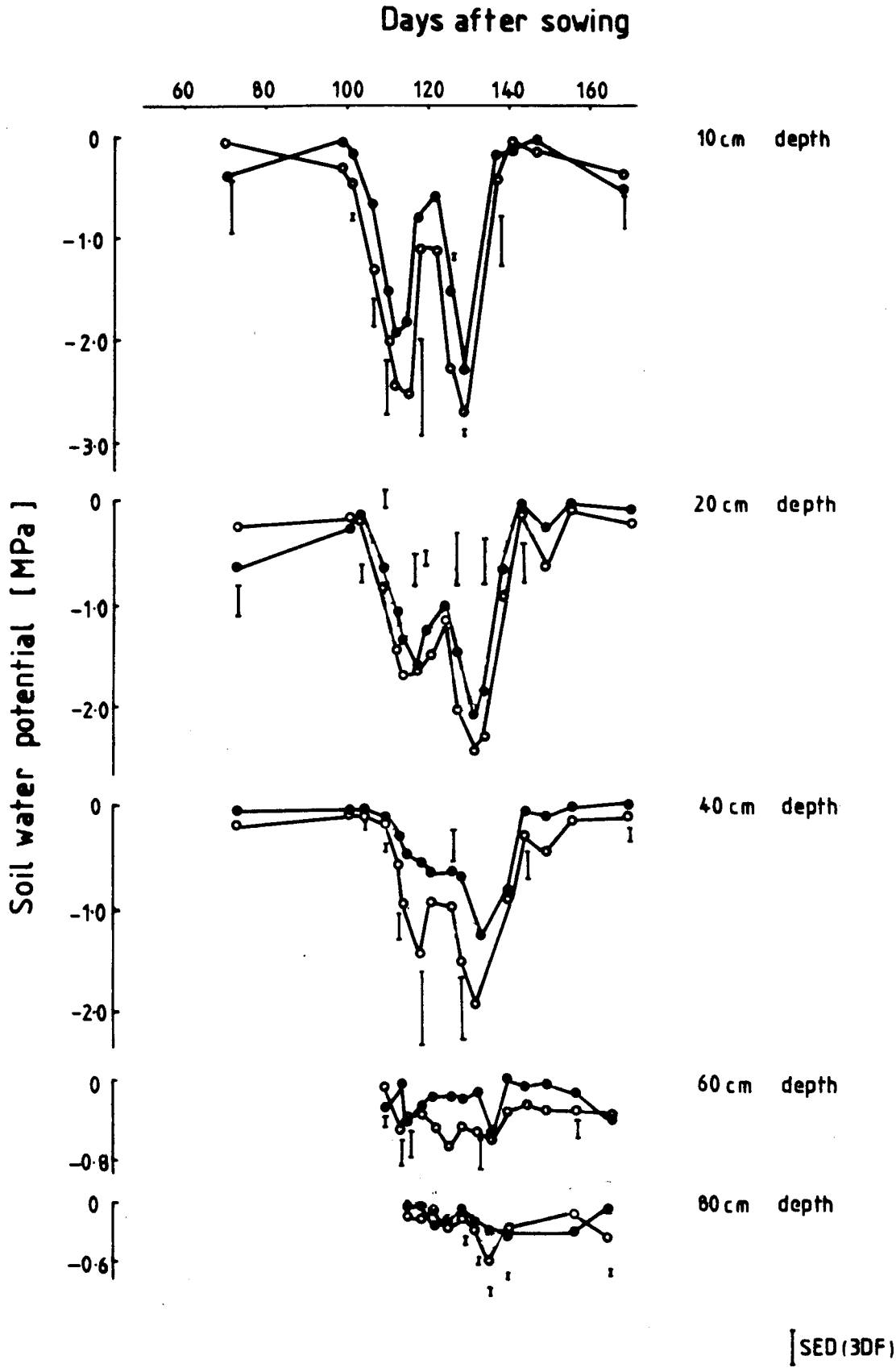
Similarly in 1984, compaction generally delayed soil drying and reduced the extent of water use in all crops (Figure 7.9).

In field beans, drying began at the end of June, 100 days after sowing, and rapidly reached an initial minimum water potential within 13 days in the top 20 cm of compact soil and in the top 40 cm of the control. Then rain penetrated the soil and drying did not recommence until 20th July (120 days after sowing) in the surface 20 cm and a few days later, deeper in the profile. The water potentials fell rapidly to the minima seven days later and were progressively greater down the profile. Soil drying reached 80 cm in the control treatment, whereas drying was limited to 60 cm in the compact crop. At the end of July rain rewetted the profile to 60 cm and this was also apparent, though to a lesser extent, in the partitioned soil moisture deficit data (Figure 7.6(a)).

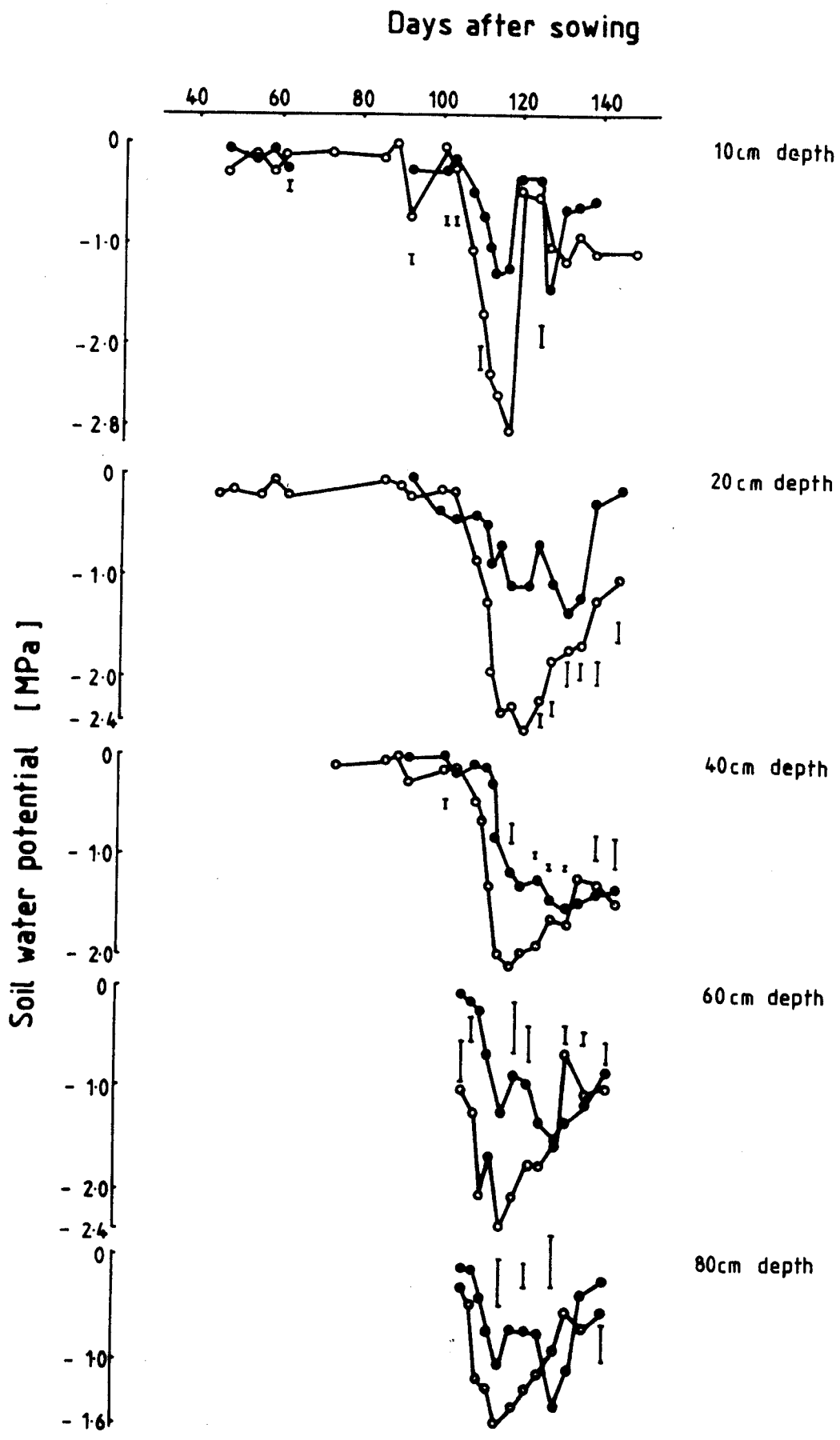
In spring barley, compaction delayed the onset of drying below 20 cm depth and also delayed, by 14 days, the attainment of minimum water potentials, which were consistently higher at all depths in the compact treatment. The partitioned moisture deficit data (Figure 7.6(b))

Figure 7.9 The influence of soil compaction on the soil water potential at selected depths under field beans (A), spring barley (B) and sugar beet (C) in 1984. Control (o); Compact (●)

[A]

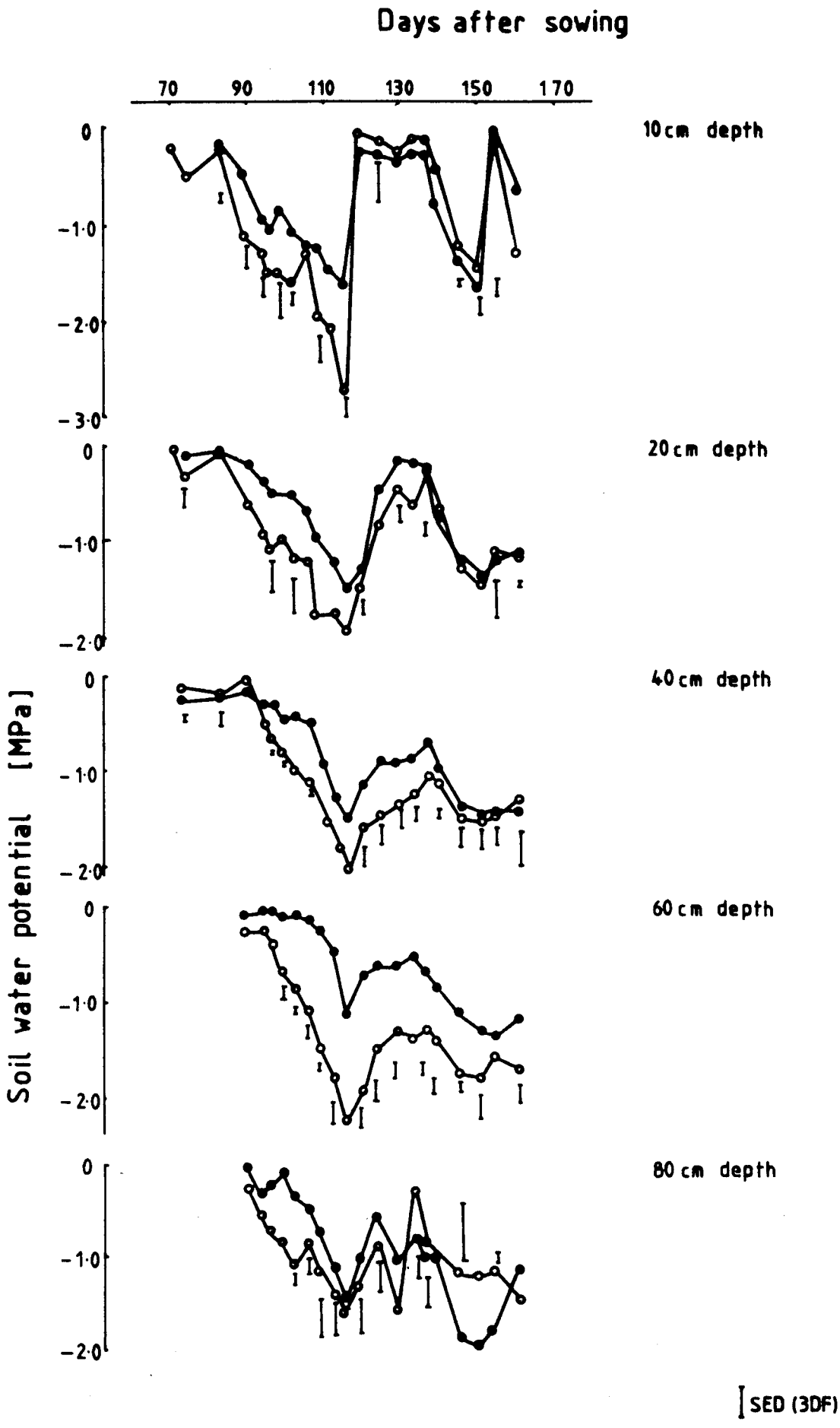

Days after sowing
60
80
100
120
140
160
Soil water potential [MPa]
0
-1·0
-2·0
-3·0
10 cm depth
20 cm depth
40 cm depth
60 cm depth
80 cm depth
-0·8
-0·6
SED (3DF)

[B]


Days after sowing
40
60
80
100
120
140
Soil water potential [MPa]
0
-1·0
-2·0
-2·8
10cm depth
0
-1·0
-2·0
-2·4
20cm depth
0
-1·0
-2·0
40cm depth
0
-1·0
-2·0
-2·4
60cm depth
0
-1·0
-1·6
80cm depth

I SED (3DF)

[C]


Days after sowing
70
90
110
130
150
170
10 cm depth
20 cm depth
40 cm depth
60 cm depth
80 cm depth
Soil water potential [MPa]
0
-1·0
-2·0
-3·0
SED (3DF)

did not show any rewetting below 30 cm, despite soil psychrometer evidence to the contrary. The difference can be explained in several ways: The shallow moisture release curve of this soil may have enabled thermocouple psychrometers to detect very slight profile rewetting; psychrometers also probably measured increased potentials as a result of some distillation of water vapour at depth, as reported by Gregory, McGowan and Biscoe (1978); a recent theory suggests that roots at depth may increase in water content following surface wetting and that psychrometers may record increased water potential due to 'wet' roots growing close to the instruments (McGowan M., personal communication, 1985).

There was a different pattern of rewetting and drying between the spring barley and the field beans. Only the first of the two phases of rewetting and drying shown in the field bean data was found in the control barley data. The reason could possibly be that senescence was more advanced in the control crop after 115 days after sowing, but the compact treatment was still then extracting water. This suggestion is strengthened by the fact that the compact crop had a marginally greater evaporation rate (Figure 7.1) and also sustained a larger green area per plant (Figure 5.4) after this date. The delayed senescence observed in compact barley crops was masked in the leaf area index data (Figure 5.3) by the population effect.

In sugar beet drying began towards the end of June, 82 days after sowing, in the 10 cm and 20 cm horizons and towards the middle of July, 98 days after sowing, at the lower depths in the profile. There was evidence of a delay in the commencement of drying by the compact crop below 60 cm. The minimum soil water potentials were achieved quickly and on

the same day (115 days after sowing) for all measured depths. Minimum potentials were lower in the surface horizons as expected and higher in the compacted soil. Rain at the end of July raised potentials at all depths, thus conflicting with the soil moisture deficit data (Figure 7.6(c)) which indicated that rewetting was confined to the top 30 cm. The increase in water potential at lower depths can largely be explained by the reasons discussed previously. Further drying occurred towards the end of August, 136 days after sowing, to achieve a second 'minimum' potential at the beginning of September, 150 days after sowing.

Crop differences were not as large as those found in 1983. Sugar beet and spring barley developed uniformly low potentials down the profile, while field beans achieved only limited drying below 40 cm.

7.3.6 Crop Evaporation in 1983 and 1984 and Drainage in 1984

The total water use can be derived by summing the cumulative soil moisture deficit and the accumulated rainfall; results therefore have been anticipated in Sub-section 7.3.2. The cumulative evaporation and the Penman potential evaporation are shown in Figure 7.10 for 1983 and Figure 7.11 for 1984.

Drainage losses were negligible in 1983 but more rain occurred in 1984 after the initial soil drying period and thus a large drainage component is also shown in Figure 7.11.

Potential evaporation was estimated from daily meteorological measurements using the method reported by Penman (Ministry of Agriculture, Fisheries and Food, 1967), and is described as "the amount of water that could be evaporated by a green crop of the same colour as grass, which completely covers the ground and which has an adequate

Figure 7.10 The influence of soil compaction on the evaporation by field beans (A), spring barley (B), sugar beet (C) and grass (D) crops in 1983. Control (o); Compact (●); Penman potential evaporation (---)

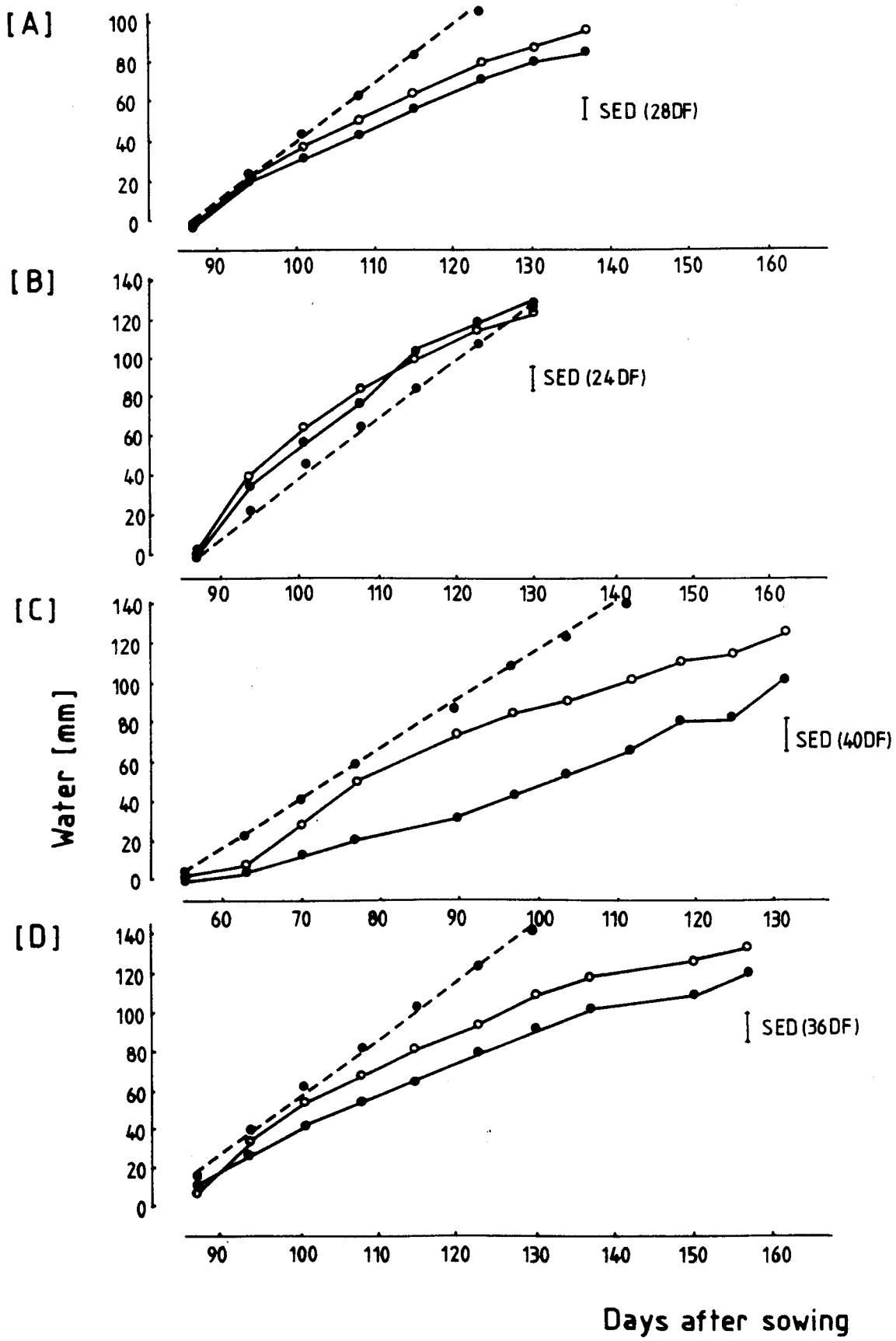
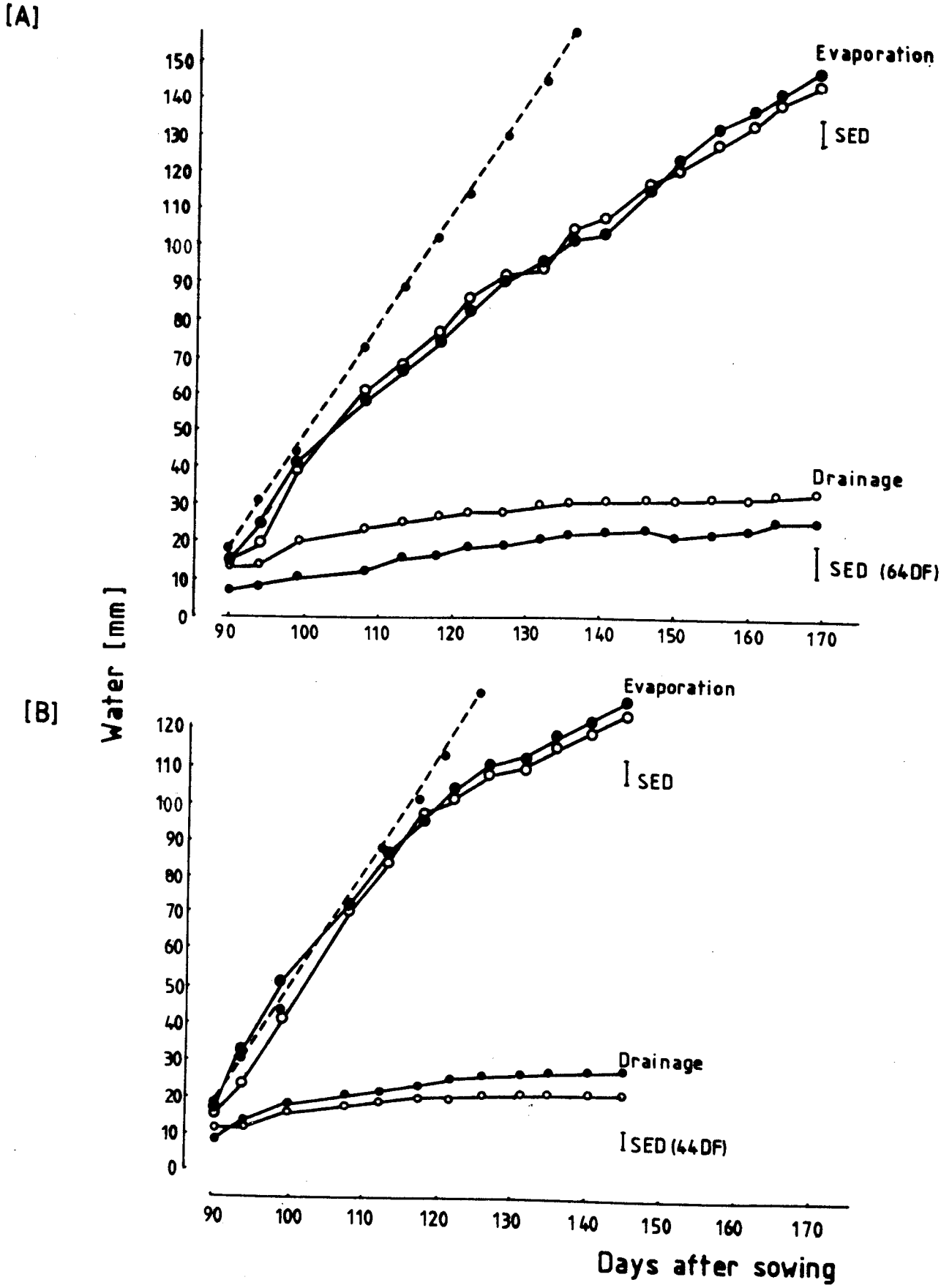
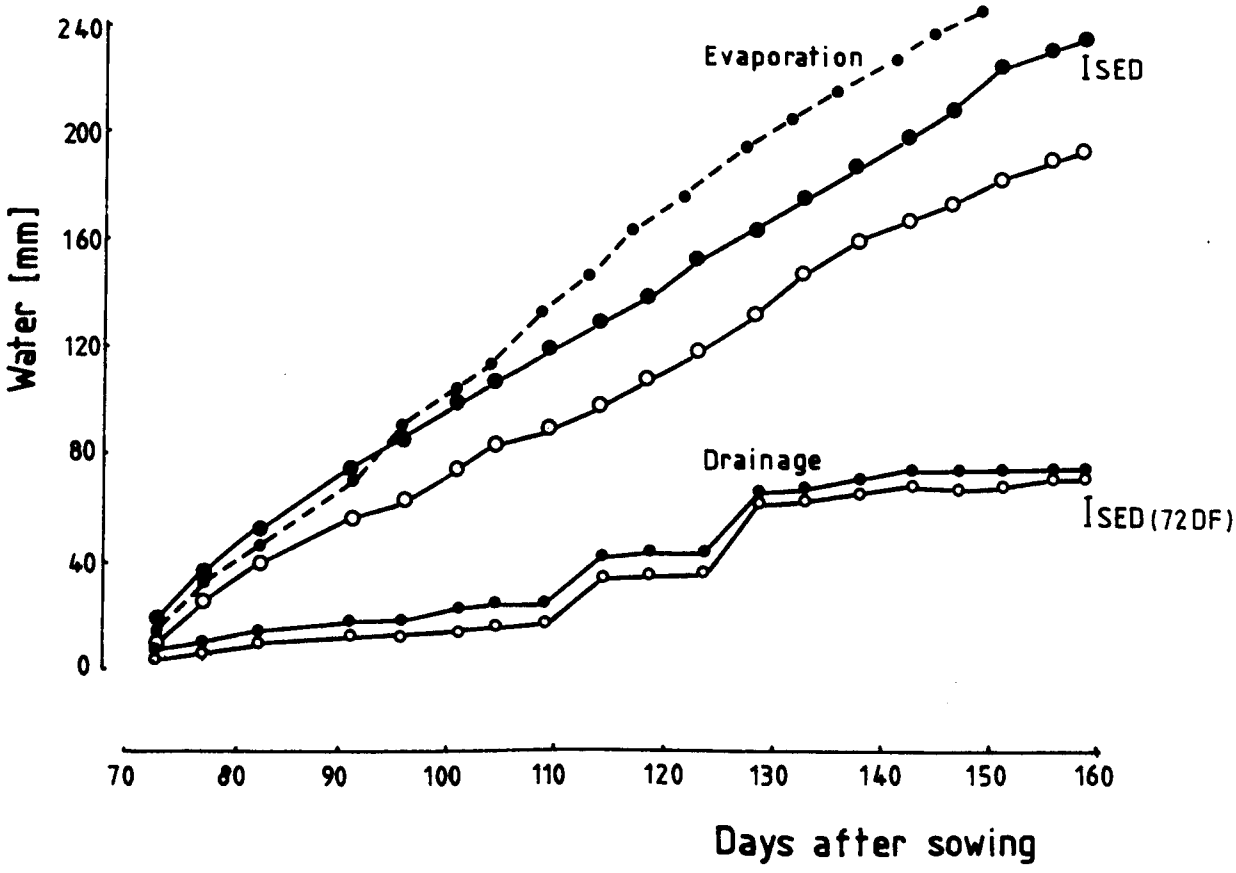

[A]
100
80
60
40
20
0
SED (28DF)
90
100
110
120
130
140
150
160
[B]
140
120
100
80
60
40
20
0
SED (24DF)
90
100
110
120
130
140
150
160
[C]
Water [mm]
140
120
100
80
60
40
20
0
SED (40DF)
60
70
80
90
100
110
120
130
[D]
140
120
100
80
60
40
20
0
SED (36DF)
90
100
110
120
130
140
150
160
Days after sowing

Figure 7.11 The influence of soil compaction on the evaporation and soil drainage under field beans (A), spring barley (B) and sugar beet (C) crops in 1984. Control (o); Compact (●); Penman potential evaporation (---)


[A]
[B]
Water [mm]
Evaporation
SED
Drainage
SED (64DF)
SED (44DF)
Days after sowing

[C]


240
200
160
120
80
40
0
Water [mm]
Evaporation
LSED
Drainage
LSED (72 DF)
70
80
90
100
110
120
130
140
150
160
Days after sowing

available supply of water at its roots". The potential evaporation was accumulated from the date at which soil drying, by the respective crop, commenced.

Compaction did not affect the water used by the field beans in either year. In 1983 the crop evaporation was similar to the potential at the beginning of soil drying but a large difference developed between actual and potential evaporation during the season. However, in 1984, field beans evaporated below the potential all season which was unlikely to be a population effect because the control treatment quickly established 95% ground cover. Similarly, Wormington (1984) found that after 90 days after sowing unirrigated crops of field beans transpired well below the Penman potential. No data is available before anthesis.

Compaction did not reduce the water use of spring barley in either year. However, the marginally greater water use by the compact crop later in the season was probably due to delayed senescence. In 1983 the crop only evaporated at a greater rate than the potential for a short period, just after the beginning of drying, and the measured evaporation remained similar to the potential evaporation for most of the season. However, in 1984 the potential exceeded the actual evaporation after 112 days after sowing due to crop senescence.

Sugar beet showed the largest change in evaporation due to compaction in both years: A 19% reduction in 1983 and an 18% reduction ($p<0.001$) in 1984. The crop evaporated below the potential throughout the 1983 season and this pattern was similar in 1984. The estimate always exceeded the compact crop water use, probably because of the large reduction in plant population and thus leaf cover. Wilting, observed in the control crop, possibly resulted in a temporary reduction in water use.

Soil compaction reduced the evaporation of the grass crop but the difference was not significant. The potential exceeded the actual evaporation throughout the season. This was possibly due to a combination of waterlogging damage at emergence and a silage cut, as previously described.

The results presented in this chapter have demonstrated how soil compaction affects the water status of the soil under field beans, spring barley, sugar beet and grass. While it has been shown that the water use of only sugar beet was significantly reduced in compact soil, it was not obvious whether soil compaction had induced conditions of plant water stress. This subject will be considered in the next chapter when the effects of compaction on the plant water status will be reported.

Chapter 8

PLANT WATER STATUS

8.1 Introduction

Leaf water potential has been directly related to crop growth and yield (Hoffman and Hilar, 1972) and has also been used as an indicator of plant water deficit (Klepper and Barrs, 1968).

The pattern of diurnal fluctuation in leaf water potential was described by Taylor and Klepper (1978) in their review of roots and water uptake. Plants suffer a reduction in leaf water potential daily as a result of water vapour diffusing out of open stomata. As the plant loses water the tissues dehydrate, turgor pressure declines and the chemical potential is thereby reduced. Water then moves from adjacent plant tissues along a path of sequentially reduced water potential. The radiant energy in the leaves increases in the morning and the leaf water potential thus decreases. In the afternoon the amount of incident radiation decreases and since there is less evaporation from the leaves, if sufficient water is available at the roots, the tissues rehydrate until they become turgid during the night.

A factor which influences the reduction in leaf water potential during a daily stress period is the supply of water from a soil to the evaporating surfaces within the leaves. However, if the flow resistance of the transport pathway is considerable then large gradients of water potential will arise during periods of rapid transpiration. This will occur even if there is no limitation on the availability of water at the roots.

This chapter investigates the effect on the plant water status of soil compaction, which acts directly on the soil-root environment.

8.2 Materials and Methods

8.2.1 Leaf and Stem Water Potential

A pressure chamber, based on the design of Turner, DeRoo and Wright (1971) and built by Wallace (1978) was used to measure the leaf and stem water potential. In 1983 and in 1984 readings were taken, on selected sunny days, every four hours from dawn until dusk.

In order to measure the leaf water potential, the last fully expanded leaf or leaflet was covered with a narrow polythene envelope so that the transpirational water loss from the leaf after cutting could be minimised. It was then severed from the plant, taken at once to the pressure bomb and trimmed to leave the main xylem vessels. The excised leaf or leaflet was placed in a split rubber stopper and approximately 1 cm was allowed to protrude at the cut end. The bung was pushed into the tapered recess in the chamber lid which was then clamped onto the body of the chamber. The pressure inside the chamber was increased at a steady rate of about 0.02 MPa s^{-1} (Wallace, 1978). The cut end of the leaf or leaflet was observed through a travelling microscope while the pressure was recorded when xylem sap appeared at the cut surface. This value (MPa) was considered to be equivalent, i.e. equal and opposite in magnitude, to the leaf water potential for that leaf and time. Four replicates of each treatment were measured.

The stem water potential was measured by covering a leaf overnight with an aluminium foil envelope lined with polythene film. This

prevented moisture loss from the leaf and therefore allowed the leaf and stem water potentials to equilibrate. The potential of the covered leaf, measured early in the morning, was considered to be the xylem potential at the time of measurement and at the point of leaf insertion into the stem (McGowan, M., personal communication, 1983). However, for cereals, this method can only be used as an approximation of stem water potential because the leaves are connected to the sheaths and not to the stem.

The pressure bomb method of measuring plant water potential is rapid and simple but it is subject to limitations, as described by Ritchie and Hinckly (1975). The principal errors are associated with the following:

1) Loss of water from the leaf between excision and measurement.
2) The amount of leaf protruding from the chamber.
3) Uncertainty associated with the hourly mean value of leaf water potential, calculated from a number of measurements made throughout that hour.
4) Uncertainty in identification of the 'end point'.
5) Withdrawal of xylem sap up the stem during excision and trimming.

8.2.2 Osmotic Potential

In 1984 young fully expanded leaves or leaflets were removed from the plants on the same day as measurements of leaf water potential were made. These leaves/leaflets were placed in vials, in liquid nitrogen to freeze the tissue rapidly and thus destroy the structure of the protoplast. The samples were stored at -15°C until the osmotic potential could be measured by means of a Wescor HR33 dew point microvoltmeter and a Wescor C-51 sample chamber.

The leaves were thawed at room temperature and pressed to exude sap onto a disc of filter paper (6 mm diameter). Thawing the leaves may have led to problems of evaporation of moisture into the air around the sample which would have reduced the osmotic potential. However, this error would have been similar for both treatments and it could therefore be ignored. The filter disc was slid inside the sample chamber and sealed in position below the hygrometer thermocouple. Sufficient time was allowed for equilibration. The microvoltmeter was then zeroed and the thermocouple was then cooled for 5-10 seconds. This produced a droplet of water on the thermocouple junction by condensation. The microvoltmeter 'dew point' mode was selected, the reading was recorded and the cooling current was switched off. The sample was then left for a further 5-10 seconds and the sequence described above was repeated until the readings became constant. The microvoltmeter reading (V) was converted to osmotic potential (ψ_π) using equation 8.1.

$$V = -7.5\,\psi_\pi \qquad 8.1$$

A full account of the theory and mode of operation of the dew point hygrometer has been produced by Wallace (1978).

8.3 Results and Discussion

The diurnal variation in leaf water potential was measured on various occasions in 1983 between 60 and 100 days after sowing. The results were similar for each observation and thus only two representative sets of data are given. Figures 8.1 and 8.2 show the diurnal variation in leaf water potential at the beginning (63/64 days after sowing) and at the end (93/96 days after sowing) of the period of measurement, repectively.

Figure 8.1 The effect of soil compaction on the diurnal variations in leaf water potential of field beans, at 64 days after sowing (A), spring barley, at 63 days after sowing (B), sugar beet, at 63 days after sowing (C) and grass, at 64 days after sowing (D), in 1983.
Control (o); Compact (●)

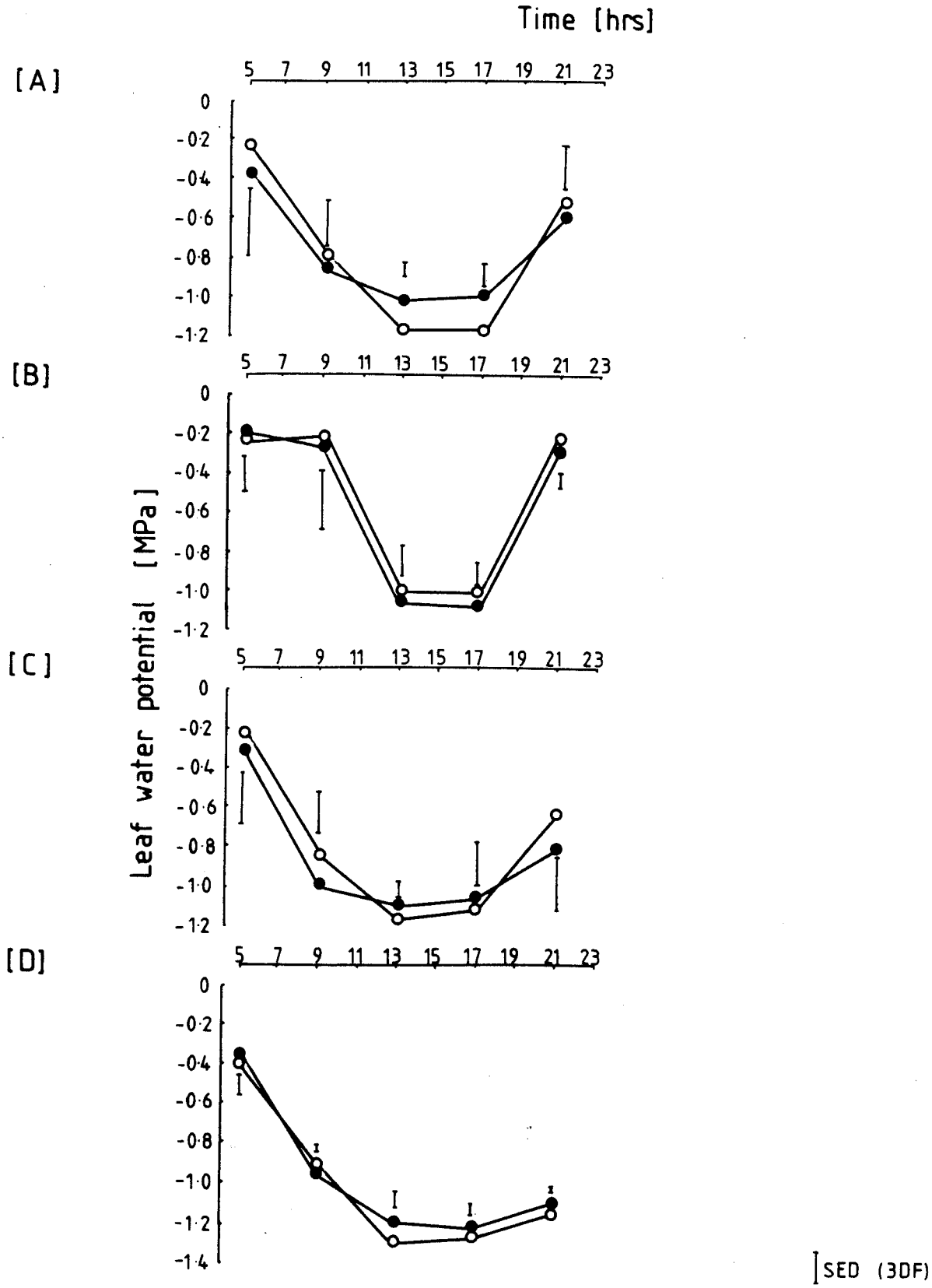
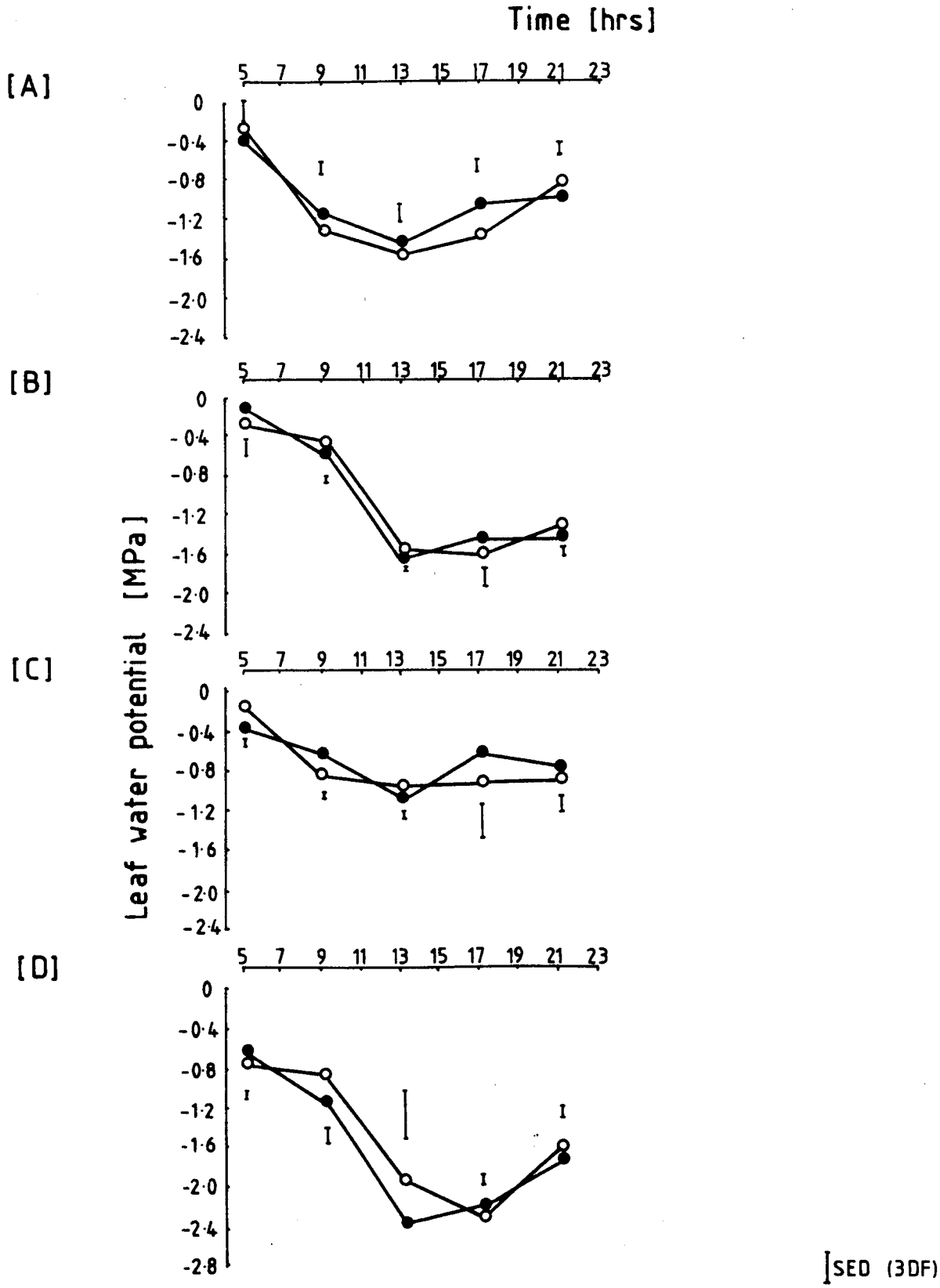

Time [hrs]
[A]
[B]
[C]
[D]
5 7 9 11 13 15 17 19 21 23
0
-0·2
-0·4
-0·6
-0·8
-1·0
-1·2
-1·4
Leaf water potential [MPa]
SED (3DF)

Figure 8.2 The effect of soil compaction on the diurnal variations in leaf water potential of field beans, at 96 days after sowing (A), spring barley, at 93 days after sowing (B), sugar beet, at 94 days after sowing (C) and grass, at 96 days after sowing (D), in 1983.
Control (o); Compact (•)


Time [hrs]
[A]
[B]
[C]
[D]
5 7 9 11 13 15 17 19 21 23
0
-0·4
-0·8
-1·2
-1·6
-2·0
-2·4
-2·8
Leaf water potential [MPa]
SED (3DF)

The leaf water potential of all the crops followed the expected diurnal trend, as described in Sub-section 8.1, but it failed to reveal any large or consistent differences between the treatments. The results support the findings of Dawkins (1982) who also reported that the diurnal change in leaf water potential was unaffected by soil compaction.

On the last sample date, 93/96 days after sowing, the leaf water potentials remained low at 2100 hr. and this reflected a greater evaporation demand and a larger soil moisture deficit than was found at the beginning of the observation period.

The diurnal changes recorded on 63/64 days after sowing were similar to those found by Wallace (1978) and by Taylor and Klepper (1978). They observed that the leaf water potential was depressed by -1.2 MPa for wheat and by -1.0 to -1.2 MPa for cotton and soybean, when growing in wet soil. In more demanding climates, Martin and Dougherty (1975) and Taylor and Klepper (1978) recorded daily changes in leaf water potential in excess of -2 MPa.

Leaf water potential has been used by many researchers to indicate the degree of crop water stress (Young and Browning, 1977) but Hsiao, Acevedo, Fereres and Henderson (1976) found that it was not the best variable to use, especially for turgor dependent processes such as growth. Kramer (1969) suggested that plant physiological processes, i.e. expansion of leaves and flowers and the opening and closing of stomata were more closely related to leaf turgor than to leaf water potential. Wallace (1978) suggested that turgor pressure was a better indicator of stomatal behaviour because calculations of plant turgor allowed for differences in osmotic potential between different leaves and also for any osmotic adaptation which occurred during water stress.

The total leaf water potential (ψ_l) has been found to be the sum of four components: osmotic potential (ψ_π), turgor pressure (ψ_p), matric potential (ψ_m) and gravitational potential (ψ_g) (Taylor and Slatyer, 1961) and these can be expressed by the Equation:

$$\psi_l = \psi_\pi + \psi_p + \psi_m + \psi_g \qquad 8.1$$

However Equation (8.1) can be simplified since ψ_m and ψ_g are usually small compared with ψ_l. The matric potential component is usually considered to be negligible because it has been shown to be only a few per cent of ψ_l under severe water stress (Wiebe, 1966; Boyer, 1967). The gravitational component is also regarded as being unimportant because it is attributed to differences in elevation and has a value of 0.01 MPa m^{-1} (Wallace, 1978).

Leaf water potential therefore is the resultant of all the factors which influence the free energy of water and two of the most important are turgor pressure and osmotic potential. When the leaf water potential is zero, the leaf is considered to be at full turgor but as the leaf water content decreases and turgor is reduced, osmotic potential also decreases owing to a change in the solute concentration. The leaf water potential is then lowered.

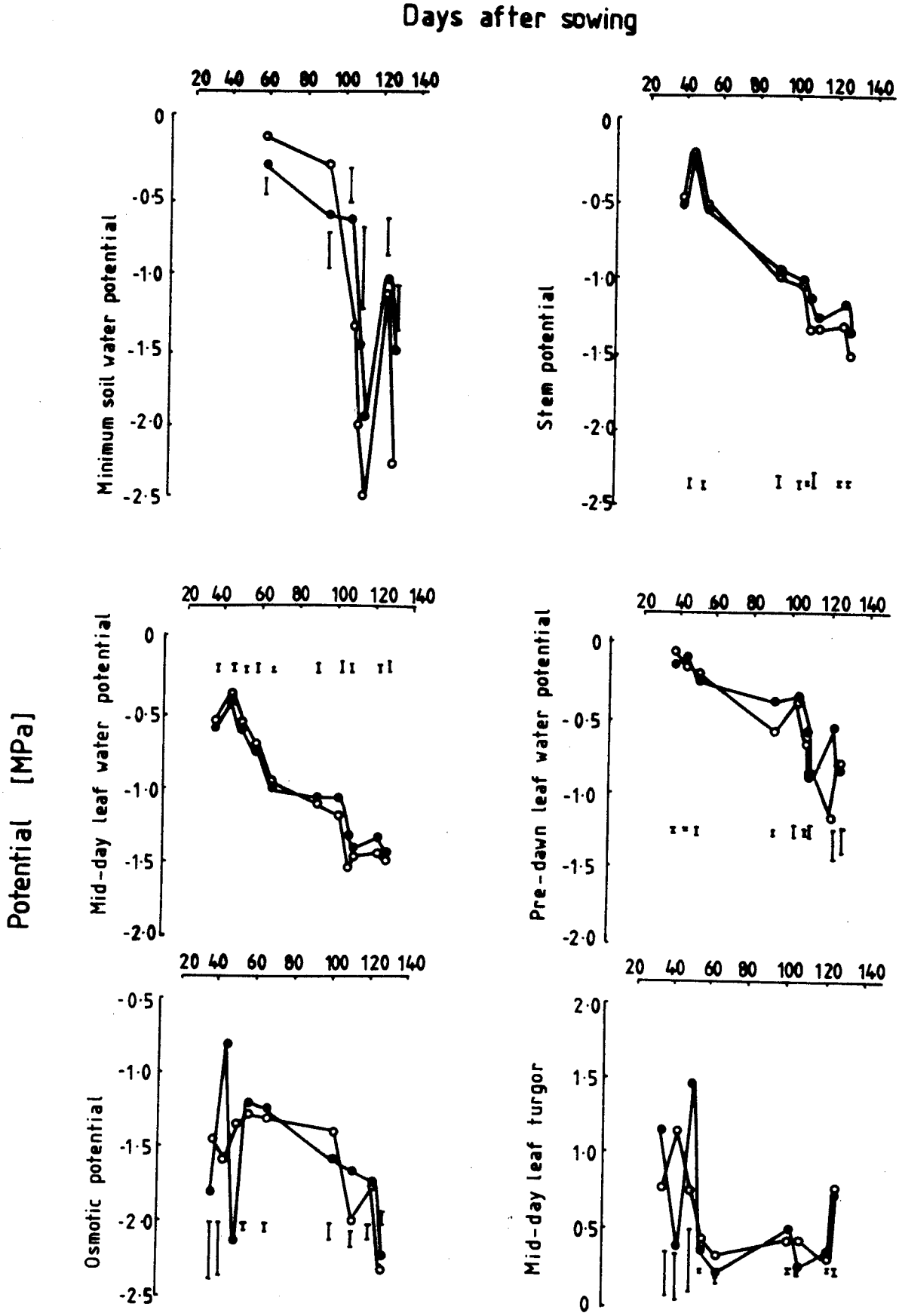
In 1984, more frequent and detailed measurements were made of the crop water balance than in the previous year. The seasonal changes in pre-dawn and mid-day leaf water potentials, osmotic potential, stem potential, minimum soil water potential and mid-day leaf turgor are given in Figure 8.3 in respect of field bean, spring barley and sugar beet.

8.3.1 The Water Balance in Field Bean

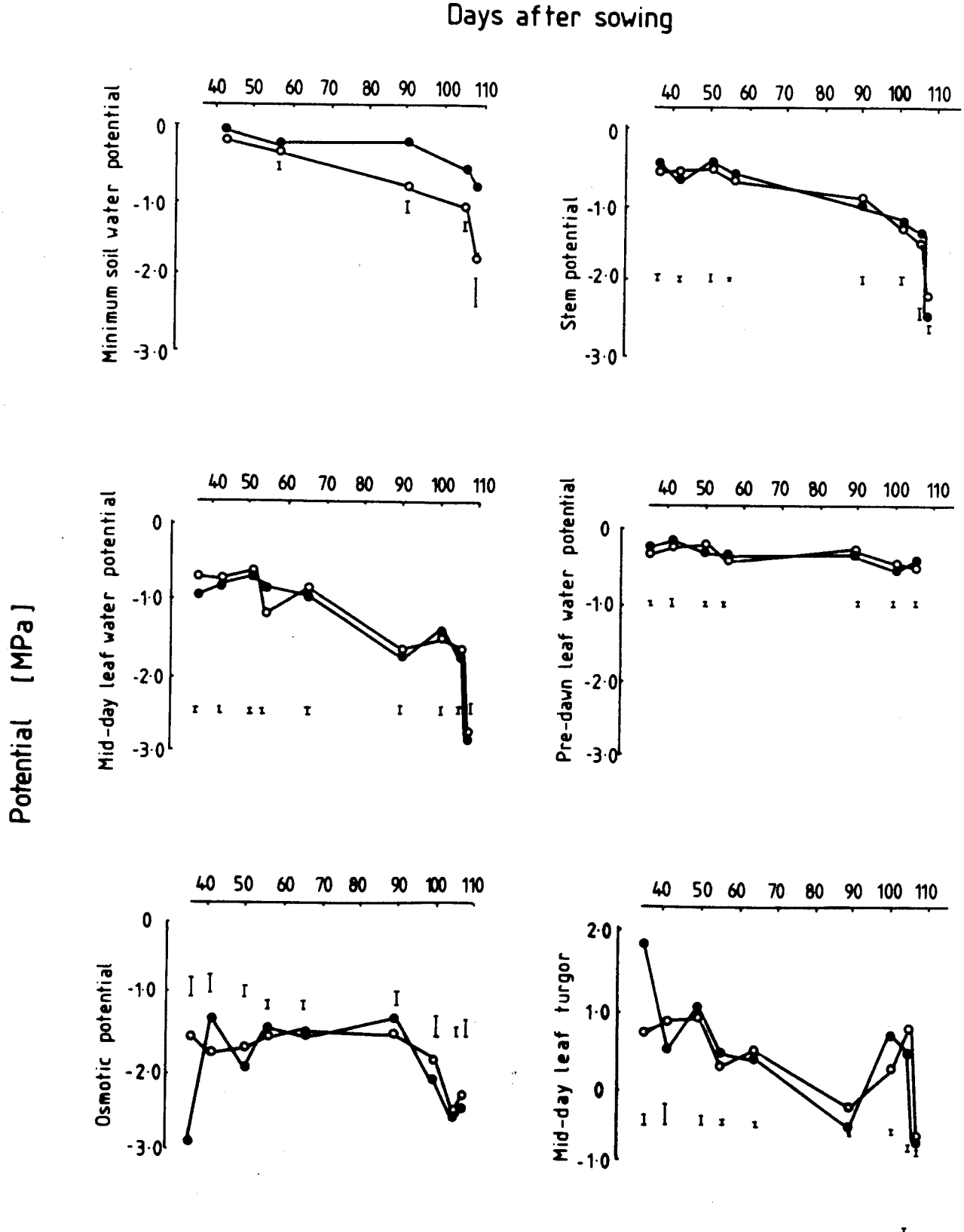
The measurements of the minimum seasonal soil water potential (Sub-section 7.3.5) did not reveal any consistent differences between the

Figure 8.3 The effect of soil compaction on the pre-dawn and mid-day leaf water potentials, osmotic potential, stem potential, minimum soil water potential and mid-day leaf turgor of field beans, spring barley and sugar beet in 1984.
Control (o); Compact (●)

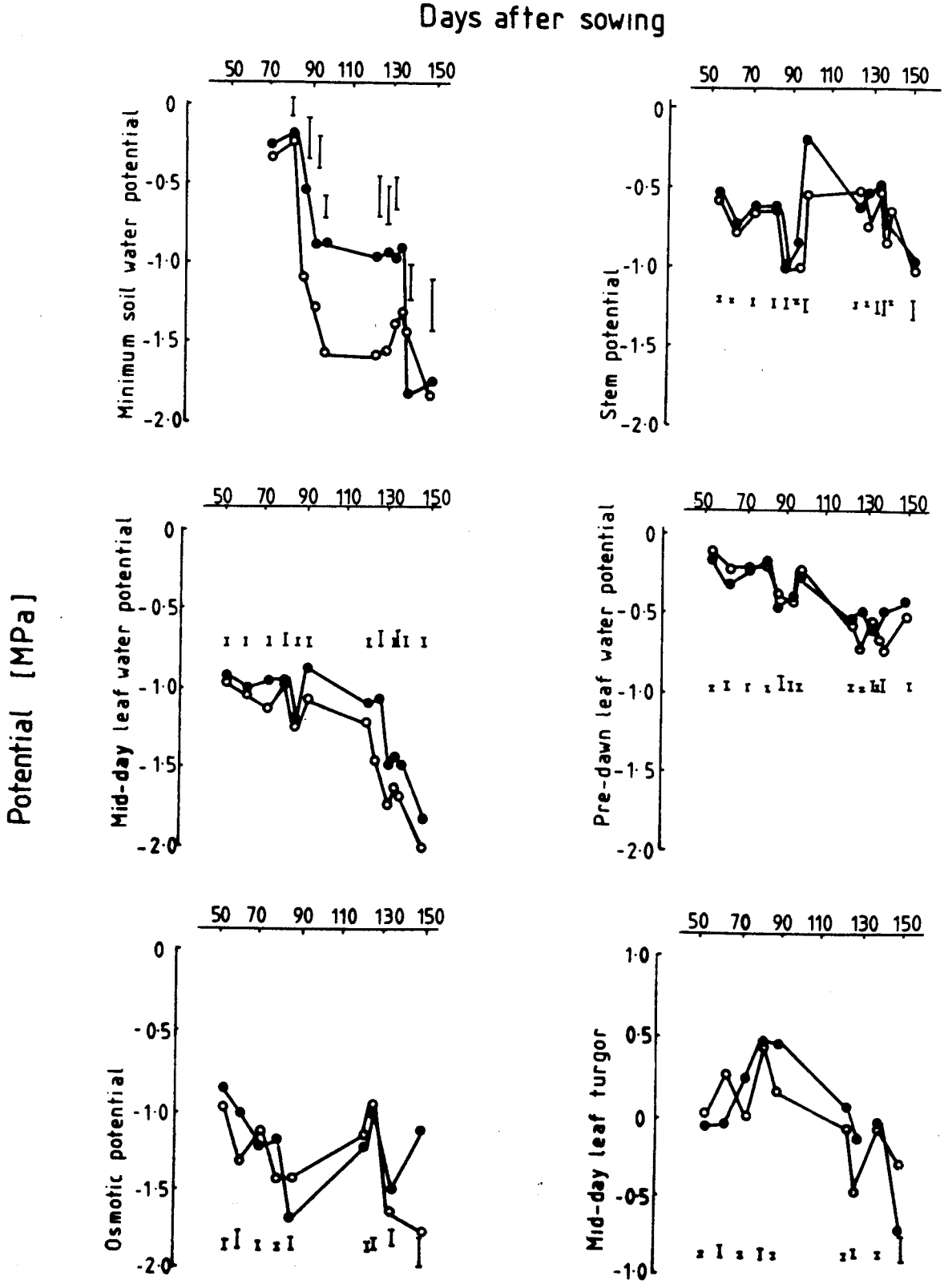
Field bean.


Days after sowing
20 40 60 80 100 120 140
Minimum soil water potential
Stem potential
Mid-day leaf water potential
Pre-dawn leaf water potential
Osmotic potential
Mid-day leaf turgor
0
-0·5
-1·0
-1·5
-2·0
-2·5
2·0
1·5
1·0
0·5
Potential [MPa]
SED (3DF)

Spring barley.



Sugar beet.



SED (3DF)

treatments. The crop grown on compacted soil initially developed a lower soil water potential but, following a period of low rainfall, the soil was dried more extensively in the control treatment.

The stem water potential and the pre-dawn and minimum leaf water potentials declined during the season in response to an increasing soil moisture deficit and to a sustained evaporative demand but no treatment differences were apparent.

A reduction in the leaf and stem water potentials, following a dry period, but without a corresponding reduction in the osmotic potential, resulted from a decline in leaf turgor during the first two weeks of May (48-60 days after sowing). However after mid-May the osmotic potential was reduced in both treatments and turgor was maintained. This substantiates the results of McGowan, Blanch, Gregory and Haycock (1984) who found that crops can maintain their turgor pressure above a critical value by lowering their osmotic potential in response to a change in the water status of the plant. Biscoe (1972) also found that for each unit decrease in the osmotic potential of sugar beet there was a concomitant decrease in the leaf water potential and so turgor pressure only decreased very gradually throughout the season.

This change in the osmotic status of the leaf may occur as a result of concentrating the existing solutes due to the reduction in leaf water potential associated with a decrease in leaf water content — a process known as leaf dehydration (Gardner and Ehlig, 1965). However, Hsiao et al. (1976) found that the leaves of maize and sorghum were able to maintain turgor by a process of osmotic adjustment, i.e. increasing the solute content of the leaf either by translocation or retention of assimilates (Biscoe, 1972). It seems therefore that both mechanisms may

exist in field crops to prevent turgor pressure falling to the same extent as leaf water potential at times of stress.

Jones and Turner (1978) found that the ability of a crop to make an osmotic adjustment depended upon the rate at which drought developed. They found that plants were able to adjust when the water potential fell slowly but turgor was often reduced when drought conditions developed quickly.

8.3.2 The Water Balance in Spring Barley

As the season progressed the control crop dried the soil to a greater extent than the compact crop (Sub-section 7.3.5) and so developed lower soil water potentials. This factor was probably related to the lower rooting density (Chapter 6) and to a reduced plant population (Chapter 4) in the compact treatments.

There was a general decline in the minimum leaf and in the stem water potentials of both treatments during the season and both fell sharply, possibly in response to a dry period, at the beginning of August (100 days after sowing) (Figure 2.1). There were however no differences between treatments.

Soil compaction did not affect the pre-dawn leaf water potential which remained high during the season, indicating that almost full turgor was regained at night despite the low minimum values of leaf and stem water potentials which developed during the day.

Leaf turgor fell gradually during the season but a sharp decrease in the osmotic potential in mid-June (90 days after sowing) increased the turgor pressure briefly. However, after 15 days, a rise in the osmotic potential, possibly owing to a transfer of material to the developing ears,

while the leaf water potential declined, produced a sharp fall in turgor. Leaf turgor was unaffected by soil compaction throughout the season.

8.3.3 The Water Balance in Sugar Beet

The minimum soil water potential decreased during the season in response to an increasing soil moisture deficit (Sub-section 7.3.5). The compact crop had a higher soil water potential than the control in mid-season (90-135 days after sowing) and therefore did not dry the soil to the same extent. This may have been attributable to the lower plant population in the compacted treatment and hence a reduced crop water use.

The stem potential and the pre-dawn leaf water potential fluctuated throughout the season but there were no treatment differences. The minimum leaf water potential declined rapidly by -1.0 MPa between the beginning of July (94 days after sowing) and the beginning of September (150 days after sowing). The plants for the compact treatment had consistently higher leaf water potentials than the control for most of the season which was a result of the higher soil water potentials found in the former crop.

The osmotic potential fluctuated throughout the season and no consistent trend developed. Consequently, turgor declined after the beginning of July (80 days after sowing) and a slight osmotic adjustment in mid-August (130 days after sowing) was sufficient to sustain leaf turgor for the remainder of the season. Although turgor was low for both treatments, the compact crop had a higher turgor pressure than the control during most of the season. This was probably an indirect effect of compaction which produced a low plant population and thereby did not deplete the soil water

reserves to the same extent as did the control crop. Therefore individual plants from the compact treatment probably had access to more soil water reserves and they therefore sustained a greater turgor pressure than the control plants, during a dry period.

Soil compaction had no effect on the diurnal change in leaf water potential of all the crops in 1983 nor upon the seasonal variation of leaf water potential, osmotic potential or leaf turgor of either field beans or spring barley in 1984. However, the leaf water potential and the turgor pressure were higher in the compacted sugar beet treatment during most of the 1984 monitoring period.

A similar response was reported by Young and Browning (1977) who initially hypothesised that plants growing in deep tilled soils would experience a lower moisture deficit than if they were grown in a conventionally tilled soil with a plough pan. However, contrary to this hypothesis, their results suggested that lower mean leaf water potentials were produced by crops grown in deep tilled soil than by conventional tilled crops. Young and Browning (1977) reasoned that the larger plants with deeper and more extensive roots, found in the deep tilled plots, had probably placed a greater demand for water on the soil as implied by their lower leaf water potential.

Other researchers have examined the effects of soil tillage on crop water status (Ehles, Grimme, Baeumer, Stulphagel, Kopke and Bohm, 1981; Musick, Dusek and Schneider, 1981; Rowse and Stone, 1981) but they have generally failed to detect any large or consistent effect of tillage treatments on leaf water potential or stomatal conductance. This occurred even when crop yields were significantly affected by such tillage operations. These reports and the results of their work conflict with the

common suggestion that one of the major effects on crop growth from soil tillage operations is by reason of changes in crop water status.

As leaf water content decreases and leaf turgor is reduced, the plant can reduce the amount of water lost by closing its stomata. There is much variation in the reports of the 'critical leaf water potential' at which stomatal resistance increases. Turner (1974) reviewed the literature on the stomatal responses of field crops and found that the critical leaf water potential varied between species from -0.8 MPa for beans to -2.7 MPa for cotton. However, he also found that the leaf turgor pressure at which stomatal resistance increased varied only between zero and 0.2 MPa.

Boyer and McPherson (1975) studied the photosynthesis of many species and found that in every instance the photosynthetic behaviour paralleled the stomatal behaviour. They also found that photosynthetic decline was greatest between leaf water potentials of -1.0 MPa and -2.0 MPa. It is therefore probable that all the crops may have developed water deficits, during 1984, great enough to increase the stomatal resistance of both treatments and hence limit photosynthesis.

The results from both years of the investigation initially suggest that plant water status was not detrimentally changed by soil compaction. It is possible however, that small changes in leaf water potential and turgor pressure may have occurred, early in the season, and these may have been too small to be detected by the pressure bomb technique but were large enough to affect leaf expansion. This subject will be discussed further in the next chapter.

Chapter 9

FINAL DISCUSSION

The results of this study indicate that the severity of a crop's response to topsoil compaction is primarily dictated by the environment, and in particular by the distribution of rainfall. In 1983, the soil was moist at the time of emergence of the field beans and the spring barley and then compaction did not reduce the plant population. In contrast, the sugar beet crop was sown 60 days later and since the rainfall was low at the time of emergence, it suffered a large reduction in plant numbers. As the soil began to dry the individual plant performance of the compact field beans and the sugar beet was impaired. However, in the same season the growth and yield of spring barley were not affected by compaction. From these observations it is possible to deduce an order of sensitivity of the crop yield to soil compaction, and in 1983 it was: spring barley $<$ field beans $<$ sugar beet.

The sensitivity of the crop to soil compaction in that season was related to the inherent root length density of the crop species. In compacted soil the total root length of spring barley was seven times greater than that of sugar beet and ten times greater than that of field beans. Previous field studies and theoretical arguments (McGowan et al., 1984) have indicated that, in general, cereals may produce more roots than are necessary for efficient water uptake and that some reduction in root density is possible without affecting the plant water status or crop transpiration. Reductions in root systems appear to be more critical where the inherent rooting density is already low, as for example, in field beans and sugar beet, especially when potential transpiration rates are high.

In 1984, the rainfall was low during the emergence of each crop and a large reduction in plant population, as a result of soil compaction, was recorded for all these crops. Following emergence the rain was plentiful throughout the season, and the compact crops compensated for their low plant numbers by producing a greater final yield per plant than the control. As before, an order of sensitivity to soil compaction can be deduced. In 1984, this was: spring barley $\approx$ field beans $<$ sugar beet.

The results of the 1984 trial thus indicate that the effect of topsoil compaction on crop yield was due principally to a reduction in plant population while the main effect on plant development arose as a result of a delay in the emergence of the compact crop.

The role of soil moisture in determining the effect of compaction on crop growth has been reported by many researchers. Trouse (1971) found that both compact soil with an even distribution of water and compacted but adequately aerated, wet soil may show no detrimental reaction to plant development. Furthermore, Goss (1974) reported that changes in the form of the root system, resulting from mechanical impedance, did not impair the ability of the plant to absorb nutrients from the soil if soil water was plentiful. In agreement with the results reported in this thesis, researchers have found that soil compaction is most likely to reduce seedling emergence if the soil is dry (Hanks and Thorpe, 1957; Dawkins, 1982), so that the soil strength is increased.

In view of these findings, it is recommended that future experiments should study the effect of frequent applications of irrigation over the emergence phase in order to reduce the soil strength and thereby prevent the large reductions in plant population which are usually associated with soil compaction. If this further research proves beneficial,

the technique would be of immediate value as management practice on soils which are prone to topsoil compaction and capping.

Many researchers have suggested that the effect of soil compaction on crop growth is a result of a limited uptake of soil water and nutrient reserves (Trouse and Humbert, 1961; Fisher, Gooderham and Ingram, 1975; Hebblethwaite and McGowan, 1980). Furthermore, changes in root morphology, such as distorted cortical cells and compressed intercellular spaces (Goss and Walter, 1969; Baligar, Nash, Hare and Price, 1975), due to soil compaction would suggest a greater resistance to water and nutrient flow into the roots. Indeed, Schumacher and Smucker (1981) reported that mechanical impedance, simulated by tightly packed glass beads, resulted in the loss of the internal airspace of drybean roots and a consequent reduction in root porosity. They suggested that it could decrease the cross-sectional area available for oxygen diffusion and thereby interfere with water uptake.

However, the results of the field trial did not support the hypothesis that the compact crops were suffering from water stress. Furthermore, the root resistance to water flow (Table 9.1), calculated from the 1984 trial data of plant water potential, water use and root length (D. Hector, unpublished data) did not reveal any consistent trends to suggest that compaction had increased the root resistance to water flow.

Further evidence to reject the hypothesis that water stress is involved in the response of crops to soil compaction is the fact that compaction was found to delay crop senescence whereas many workers have shown that water stress promotes leaf senescence (Finch-Savage and Elston, 1976; Elston, Karamanos and Wadsworth, 1978; Karamanos, 1978).

The results demonstrate that the primary adjustment of each crop to adverse soil physical conditions is a reduction in the leaf area expansion. The production of smaller leaves reduces crop transpiration and enables individual plants to maintain leaf water status and thereby survive an impaired ability of the root system to explore the soil profile and extract soil water. A reduced leaf area results in a lower ground cover and a reduced light interception and hence a decline in dry matter accumulation and yield.

Table 9.1 The root resistance to water uptake of field beans, spring barley and sugar beet as influenced in 1984 by soil compaction (D. Hector, unpublished data)

Depth (cm)	Root resistance MPa m^{-3} water m^{-1} root s^{-1}		Days after sowing
	Control	Compact	
Field bean			
0 - 30	9.83×10^{10}	1.33×10^{10}	86 - 136
30 - 60	5.60×10^{11}	4.72×10^{10}	99 - 136
60 - 90	1.04×10^{10}	-	108 - 136
Spring barley			
0 - 30	3.36×10^{11}	6.69×10^{10}	69 - 133
30 - 60	5.28×10^{11}	9.09×10^{10}	83 - 133
60 - 90	2.18×10^{11}	3.76×10^{10}	102 - 133
Sugar beet			
0 - 30	4.77×10^{10}	7.37×10^{10}	86 - 146
30 - 60	1.46×10^{11}	-	95 - 146

The importance of early leaf growth in maximising the light interception from bright weather in May, June and July in order to produce high yields has been emphasised by many researchers (Scott et al., 1973;

Gallagher and Biscoe, 1978; Hawkins, 1982). Indeed, Milford and Riley (1980) identified the slow initial leaf expansion of sugar beet, during those months when the radiation receipts were greatest, as a major potential source of lost yield. Similarly, Hawkins (1982) found that if early growth is slow and occurs during a period of bright sunlight, the potential loss of dry matter can be quite significant. For a crop such as sugar beet, which is harvested in the vegetative condition, it may represent a direct loss of potential yield. However, a crop which changes to reproductive growth may not display this relationship because the assimilate which is produced during the vegetative phase may not be translocated into harvestable organs.

What therefore initiates the production of a smaller leaf area? Is this an adaptive response of plants, due to impaired plant water status or nutrient availability at the time of crop emergence or is a direct messenger from the root to the shoot involved? Although leaf water potential measurements failed to reveal any significant differences between plants grown on compacted and on non-compacted soils, all these measurements were made upon crops which were at least several weeks old, by which time the plants had regulated their water use by production of smaller leaves.

Furthermore, the pressure bomb apparatus which was used in the 1983 and 1984 trials to measure leaf water potential may not be sufficiently accurate to identify the small changes in turgor pressure which might account for a reduction in the leaf expansion. A 0.1 MPa reduction in turgor pressure is enough to reduce the leaf expansion rate by 10% in groundnut (Black, C., personal communication, 1985). However this difference would be very difficult to establish experimentally in the field owing to experimental errors and variation among the leaves.

Although the measurements of nutrient content, taken in 1984, failed to discern any consistent differences between the treatments in the leaf nitrogen content, no analysis was made directly after crop emergence. Milford, Pocock, Riley and Messem (1985) found that if a sugar beet crop were deprived of nitrogen, the leaf size was reduced by a decrease in the absolute rate of leaf expansion. In addition, Morton and Watson (1948) found that an increase in the size of sugar beet leaves after nitrogen application was associated with a stimulation of meristematic activity and an increased number of cells within the lamina.

Since the greatest resistance to penetration was found to be between a depth of 7.0 and 10.0 cm (Sub-section 3.3.6), it is possible that the initial root growth may have been sufficiently impeded to restrict the uptake of nitrogen into the leaves, in the period just after emergence. Once the roots had penetrated this barrier the uptake of nitrogen may not have been affected by compaction. However this hypothesis requires further experimentation in order to verify whether the leaves of compact plants contain less nitrogen than those of the control, at the beginning of the season. The same hypothesis may account for the slow initial expansion of the leaves in the compact treatment.

Since the major effect of soil compaction on crop growth is probably the result of a reduction in the individual leaf size, future research should investigate methods of expanding artificially the leaf area by chemical means. Gibberellic acid (GA_3) would appear to be the most appropriate compound since it is know to increase leaf size (Humphries and French, 1965). However leaves expanded by GA_3 treatment are often thinner (Humphries and French, 1965) and contain less chlorophyll per unit area (Wolf and Haber, 1960) than untreated leaves. The increased area

might therefore be offset by a reduction in the photosynthesis per unit area. Furthermore, an increase in the size of individual leaves has been found to be compensated for by a reduction in the rate of new leaf emergence (Lester, Carter, Kelleher and Laing, 1972). However not all the research in this area on GA_3 treatments has yielded negative results and the chemical compound warrants further study (Hawkins, 1982).

It is possible that the response of the crop to soil compaction may be a result of a signal produced in the roots. This signal might take the form of a plant growth substance since it is known that abscisic acid (ABA) and Indole-3-acetic acid (IAA) can influence root growth (Lachno, 1983). Indeed there is evidence to suggest a role for endogenous ethylene in the response of root growth to soil compaction, specifically in mechanical impedance (Kays, Nicklow and Simons, 1974; Barley, 1976; Goss and Russell, 1980; Lachno, Harrison-Murray and Audus, 1982; Dawkins, Roberts and Brereton, 1983).

A notable response of the root system to mechanical impedance is a reduction in the longitudinal extension and an enhanced lateral expansion of cells behind the root tip. Such a morphological modification to plant tissue can be seen in the hypocotyls of sugar beet seedlings which were recovered from compacted soil (Plate 9.1). This reorientation of cell growth occurs without a corresponding increase in cellular volume (Wilson, Robards and Goss, 1977). A morphological change of this character has also been found to be initiated by exposure of pea epicotyls to the plant growth substance ethylene (Osborne, 1976).

Furthermore the kinetics of the ethylene inhibition of root elongation (Osborne, 1976) and the response to mechanical impedance (Goss, 1974) are similar; both reactions occurring within one hour of treatment.

Plate 9.1 The swollen hypocotyls of sugar beet seedlings grown in compacted soil

Further evidence to illustrate the role of ethylene has come from the work of Goeschl, Rappaport and Pratt (1966) who found that mechanical impedance promoted ethylene production by pea epicotyls. This response was also found in potato sprouts (Catchpole and Hillman, 1976). In support of these observations Samimy (1980) reported that the roots of cultivars of soybean, which were differentially sensitive to soil compaction, produced different amounts of ethylene when their growth was impeded.

Kays et al. (1974) measured an increased level of ethylene production when the root growth of beans was impeded by an immobile barrier. This approach however did not closely resemble root penetration through compacted soil because the root tip experienced only a unilateral resistance to growth. Further work is required to devise a system which accurately imitates the impeding action of soil compaction but which also permits the level of ethylene production to be measured.

Of considerable interest are the observations of Goss and Russell (1980) who found that the removal of the root cap reduced the sensitivity of maize roots to mechanical impedance. It is therefore conceivable that the root cap is the site of environmental perception of root tissue and environmental stimuli are transmitted from the cap to other parts of the root system. Certainly the root cap plays an important role in the transmission of gravitropic and phototropic stimuli to the rest of the root (Wilkins, Larque-Saavedra and Wain, 1974). If such a hypothesis is correct, the elevated ethylene levels reported after compaction may originate from the cap cells.

Ethylene rapidly diffuses in air and therefore in order to measure the levels of gas produced, the tissue must be contained and the gas

permitted to accumulate (Ward, Wright, Roberts, Self and Osborne, 1978). Although this technique permits an accurate and reproducible determination of ethylene production, it does not identify the site of the production of the gas. An indirect estimate of ethylene production by plant tissue could be obtained by determining the amount of the ethylene precursor 1-aminocyclopropane-1-carboxylic acid (ACC) (Adams and Yang, 1979) or its conjugate malonyl ACC (MACC) (Hoffman, Yang and McKeon, 1982).

In order to investigate whether ethylene acts as a secondary messenger in the response of roots to compaction, it should be possible to diminish its symptoms by inhibiting the synthesis of ethylene or blocking its site of action. This approach has been taken by Wilkins, Wilkins and Wain (1977) using the chemical 3,5, Diiodohydroxybenzoic acid (DIHB) which has some effect on both of the processes mentioned above. The chemical was used in the 1983 field trial, but without success, in an attempt to reduce the detrimental effects of soil compaction on crop growth. However, more work is required to assess the rate and method of application of the chemical in a field situation.

Greater success may be achieved in this area by using Amino-ethoxy-vinyl glycine (AVG) which has been found to block specifically ethylene biosynthesis (Lieberman, 1979) or by using silver thiosulphate which has been demonstrated to interfere with the site of action of ethylene.

This area of research, at the physiological level, may provide information of direct benefit to growers. If ethylene is found to be the causal agent in the response of crops to soil compaction and if a compound were found to suppress ethylene levels or its effects, then it might be possible to counteract temporarily the effects of compaction by spraying

the chemical on an area of ground subjected to wheeling damage at the beginning of the season.

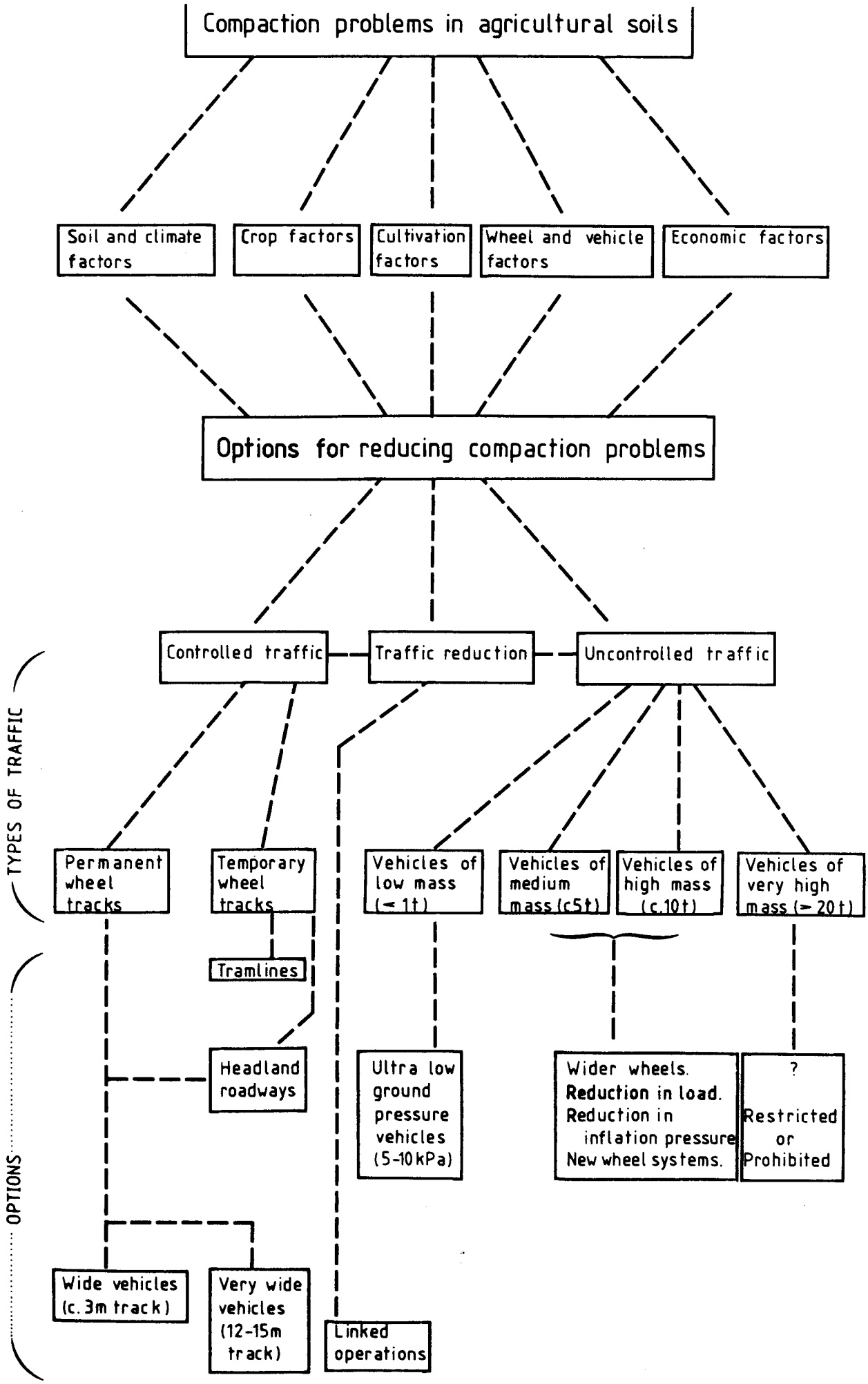
However it is clear that other lines of inquiry must also be investigated since chemical treatment would be of little advantage if the increased soil strength, caused by soil compaction, prevented seedling emergence. Recent work by Ghaderi, Smucker and Adams (1984) investigated the possibility of selecting dry bean (Phaseolus vulgaris L.) for tolerance to soil compaction. These workers investigated the change in the pattern of phenotypic correlation, involving yield and its components under compacted and non-compacted soil conditions, and they also formulated a selection strategy for maximising crop productivity and tolerance to soil compaction. Ghaderi et al. (1984) concluded their report by stating that "while we have emphasised the importance of breeding for tolerance to soil compaction, we do not wish to overlook the soil management systems that minimize its adverse effects".

The results of the 1983 and 1984 trials have suggested that a reduction in plant population is the most damaging effect on crop yield of soil compaction. Soil management practices which reduce unnecessary field traffic and the avoidance of tillage when the soil is wet could result in an immediate alleviation of the problem of soil compaction. Indeed, the work of Soane, Dickson and Blackwell (1979), who reported the options for reducing compaction under wheels (Figure 9.1) must prove to be a valuable message to growers.

The future application of this thesis must lie in the introduction of management practices which will reduce the incidence of soil compaction. Strict adherence to these practices will enable the farmer to increase output in relation to fixed costs and thereby increase farm profits.

Figure 9.1 Simplified diagrammatic representation of some of the options available for reducing compaction in relation to the factors affecting the cultivation system as a whole

(after Soane et al., 1979)


Compaction problems in agricultural soils
Soil and climate factors
Crop factors
Cultivation factors
Wheel and vehicle factors
Economic factors
Options for reducing compaction problems
Controlled traffic
Traffic reduction
Uncontrolled traffic
TYPES OF TRAFFIC
Permanent wheel tracks
Temporary wheel tracks
Vehicles of low mass (< 1t)
Vehicles of medium mass (c5t)
Vehicles of high mass (c.10t)
Vehicles of very high mass (> 20t)
Tramlines
Headland roadways
Ultra low ground pressure vehicles (5-10kPa)
Wider wheels.
Reduction in load.
Reduction in inflation pressure
New wheel systems.
?
Restricted or Prohibited
OPTIONS
Wide vehicles (c. 3m track)
Very wide vehicles (12-15m track)
Linked operations

BIBLIOGRAPHY

BIBLIOGRAPHY

ABO EL-ZAHAB, A.A., Al-BABAWY, A.A. and NIDAWY, I.S. (1981). Density studies on faba beans (Vicia faba L.). II. Growth parameters. Z. Acker- und Pflanzenbau (Journal of Agronomy and Crop Science) 150, 303-312.

ADAMS, D.O. and YANG, S.K. (1979). Ethylene biosynthesis : identification of 1-aminocyclopropane carboxylic acid as an intermediate in the conversion of methionine to ethylene. Proceedings of the National Academy of Science 76, 170-174.

ADCOCK, M.E. and LAWES, D.A. (1976). Self-fertility and the distribution of seed yield in Vicia faba L. Euphytica 25, 89-96.

ANDERSON, G.C., PIDGEON, J.D., SPENCER, H.B. and PARKS, R. (1980). A new hand-held recording penetrometer for soil studies. Journal of Soil Science 31, 279-296.

ARCHER, J.R. (1979). Water retention characteristics. In: Archer, J.R. and Marks, M.J. (Eds.) Techniques for measuring soil physical properties. ADAS Advisory Paper No.18, pp. 4-6. London, HMSO.

ASPINALL, D. (1961). The control of tillering in the barley plant. I. The pattern of tillering and its relation to nutrient supply. Australian Journal of Biological Science 14, 493-505.

AUSTIN, R.B. and BLACKWELL, R.D. (1980). Edge and neighbour effects in cereal yield trials. Journal of Agricultural Science, Cambridge 94, 731-734.

BAKERMANS, W.A.P. and DeWIT, C.T. (1970). Crop husbandry on naturally compacted soils. Netherlands Journal of Agricultural Science 18, 225-246.

BALIGAR, V.C., NASH, V.E., HARE, M.L. and PRICE, J.A. (1975). Soybean root anatomy as influenced by soil bulk density. Agronomy Journal 67, 842-844.

BALL, B.C. and O'SULLIVAN, M.F. (1982). Soil strength and crop emergence in direct drilled and ploughed cereal seedbeds in seven field experiments. Journal of Soil Science 33, 609-622.

BARLEY, K.P. (1962). The effects of mechanical stress on the growth of roots. Journal of Experimental Botany 13, 95-110.

BARLEY, K.P. (1965). The effect of localized pressure on the growth of the maize radicle. Australian Journal of Biological Science 18, 499-503.

BARLEY, K.P. (1976). Mechanical resistance of the soil in relation to the growth of roots and emerging shoots. Agrochimica 20, 173-182.

BARLEY, K.P., FARRELL, D.A. and GREACEN, E.L. (1965). The influence of soil strength on the penetration of a loam by plant roots. Australian Journal of Soil Research 3, 69-79.

BAR-YOSEF, B. and LAMBERT, J.R. (1981). Corn and cotton root growth in response to soil impedance and water potential. Soil Science of America Journal 45, 930-935.

BASCOMB, C.L. (1974). Physical and chemical analyses of <2 mm samples. In: Avery, B.W. and Bascomb, C.L. (Eds). Soil Survey Laboratory Methods. Technical Monograph 6, pp. 19-20.

BATEY, T. and DAVIES, B.D. (1971). Soil structure and the production of arable crops. Journal of the Royal Agricultural Society of England 132, 106-122.

BAVER, L.D. and FARNSWORTH, R.B. (1940). Soil structure effects on the growth of sugar beet. Soil Science Society of America Proceedings 5, 45-48.

BELL, J.P. (1969). A new design principle for neutron soil moisture gauges : the 'Wallingford' Neutron Probe. Soil Science 108, 160-164.

BELL, J.P. (1973). Neutron probe practice. Report 19, Institute of Hydrology, Wallingford, UK.

BEVERIDGE, J.L., JARVIS, R.H. and RIDGMAN, W.J. (1965). Studies on the nitrogenous manuring of winter wheat. Journal of Agricultural Science, Cambridge 65, 379-387.

BISCOE, P.V. (1972). The diffusion resistance and water status of leaves of Beta vulgaris. Journal of Experimental Botany 23, 930-939.

BISCOE, P.V. (1979). Basic cereal physiology and its application to wheat. In: Course Papers : The yield of cereals. pp. 7-19. Stonleigh, National Agricultural Centre, Cereal Unit.

BISCOE, P.V., SCOTT, R.K. and MONTEITH, J.L. (1975). Barley and its environment. III. Carbon budget of the stand. Journal of Applied Ecology 12, 269-293.

BISCOE, P.V. and GALLAGHER, J.N. (1977). Weather, dry matter production and yield. In: Landsberg, J.J. and Cutting, C.V. (Eds.) Environmental effects of crop physiology. pp. 75-100. London, Academic Press.

BISCOE, P.V. and GALLAGHER, J.N. (1978). A physiological analysis of cereal yield. I. Production of dry matter. Agricultural Progress 53, 34-50.

BLACKWELL, P.S. and SOANE, B.D. (1981). A method of predicting bulk density in field soils resulting from compaction by agricultural traffic. Journal of Soil Science 32, 51-65.

BLAKE, G.R., OGDEN, A.B., ADAMS, E.P. and BOELTER, D.H. (1960). The effect of soil compaction on development and yield of sugar beet. Journal of the American Society of Sugar Beet Technology 11, 236-242.

BOUYOUCOS, G.J. (1962). Hydrometer method improved for measuring particle size distribution. Agronomy Journal 54, 464-465.

BOWEN, H.D. (1976). Correlation of penetrometer cone index with root impedance. American Society of Agricultural Engineers. Paper 76-1516. St. Joseph, MI.

BOWMAN, D.H. and KING, K.M. (1966). Determination of evapotranspiration using the neutron scattering method. Canadian Journal of Soil Science 45, 117-126.

BOYER, J.S. (1967). The matric potentials of leaves. Plant Physiology 42, 213-217.

BOYER, J.S. and McPHERSON, H.G. (1975). Physiology of water deficits in cereal crops. Advances in Agronomy 27, 1-22.

BREMNER, J.M. and JENKINSON, D.S. (1960). Determination of organic carbon in soil. I. Oxidation by dichromate of organic matter. Journal of Soil Science 11, 394-402.

BRITISH STANDARDS INSTITUTION (1975). Methods of tests for soils for civil engineering purposes. BS 1377, pp. 57-58.

CAMPBELL, G.S. (1974). A micropower electronic integrator for meteorological applications. Agricultural Meteorology 13, 399-404.

CAMPBELL, D.J., DICKSON, J.W. and HUNTER, R. (1980). Compaction by 181, 72 and 61 Kw tractors in a silt loam seedbed. Scottish Institute of Agricultural Engineering, Departmental note, SIN/312 (Unpubl.). Cited by Ball, B.C. and O'Sullivan, M.F. (1982). Soil strength and crop emergence in direct drilled and ploughed cereal seedbeds in seven field experiments. Journal of Soil Science 33, 609-622.

CAMPBELL, D.J., STAFFORD, J.V. and BLACKWELL, P.S. (1980). The plastic limit, as determined by the drop-cone test, in relation to the mechanical behaviour of soil. Journal of Soil Science 31, 11-24.

CANNELL, R.Q. (1977). Soil aeration and compaction in relation to root growth and soil management. Applied Biology 2, 1-86.

CARNES, A. (1934). Soil crusts. Agricultural Engineering 15, 167-171.

CASTILLO, S.R., DOWDY, R.H., BRADFORD, J.M. and LARSON, W.E. (1982). Effects of mechanical stress on plant growth and nutrient uptake. Agronomy Journal 74, 526-530.

CATCHPOLE, A.H. and HILLMAN, J.R. (1976). The involvement of ethylene in the coiled sprout disorder of potato. Annals of Applied Biology 83, 413-423.

CAUSTON, D.R. and VENUS, J.C. (1981). The biometry of plant growth. London, Edward Arnold.

CHANCELLOR, W.J. (1971). Effects of compaction on soil strength. In: Barnes, K.K., Carlton, W.H., Taylor, H.M., Throckmorton, R.I. and Vanden Berg, G.E. (Organ. Comm.). Compaction of agricultural soils. American Society of Agricultural Engineers, pp. 190-212. St. Joseph, MI.

CHANCELLOR, W.J. (1976). Compaction of soil by agricultural equipment. Bulletin 1881, p. 53. Division of Agricultural Science, University of California, Davis.

CHAPMAN, G.P. (1981). Genetic variation within Vicia faba. FABIS (June), p. 12.

CHILDS, E.C. (1942). Stability of clay soils. Soil Science 53, 79-92.

COOKE, G.W. (1963). Fertilizer availability. Symposium of the British Weed Control Council 2, 50-54.

DANTUMA, G., VON KITTLITZ, E., FRAUEN, M. and BOND, D.A. (1983). Yield, yield stability and measurements of morphological and phenological characters of faba bean (Vicia faba L.) varieties grown in a wide range of environments in Western Europe. Results of the EC joint faba bean trials. 2. Zeitschrift fur Pflanzenzuchtg 90, 85-105.

DARWINKLE, A. (1978). Patterns of tillering and grain production of winter wheat at a wide range of plant densities. Netherlands Journal of Agricultural Science 20, 383-393.

DAVIES, D.B. (1975). Field behaviour of medium textured and 'silty' soils. In: Soil physical conditions and crop production. Ministry of Agriculture, Fisheries and Food Technical Bulletin 29, pp. 52-76. London, HMSO.

DAWKINS, T.C.K. (1982). Soil physical conditions and the vining pea crop. Ph.D. thesis, University of Nottingham.

DAWKINS, T.C.K., ROBERTS, J.A. and BRERETON, J.C. (1983). Mechanical impedance and root growth - the role of endogenous ethylene. In: Jackson, M.B. and Stead, A.D. (Eds.) Growth regulators in root development, Monograph 10, pp. 55-69. British Plant Growth Regulator Group, Wantage.

DENNET, M.D., AULD, B.A. and ELSTON, J. (1978). A description of leaf growth in Vicia faba L. Annals of Botany 42, 223-232.

DRAYCOTT, A.P., HULL, R., MESSEM, A.B. and WEBB, D.J. (1970). Effect of soil compaction on yield and fertilizer requirements in sugar beet. Journal of Agricultural Science, Cambridge 75, 533-537.

DREW, M.C. and GOSS, M.J. (1971). Mechanical Impedance. Agricultural Research Council, Letcombe Laboratory Annual Report 1970, p. 6.

DUNCAN, W.G., SHAVER, D.N. and WILLIAMS, W.A. (1973). Insolation and temperature effects on maize growth and yields. Crop Science 13, 187-190.

DURRANT, M.J., LOVE, B.J.G., MESSEM, A.B. and DRAYCOTT, A.P. (1973). Growth of crop roots in relation to moisture extraction. Annals of Applied Biology 74, 387-394.

DVORTSOV, E.F. and POLYAK, A.Y. (1979). High powered tractors and their implements, including aspects of their impact on the soil. Economic Commission for Europe, AGRI/MECH Report 80, pp. 15. United Nations, New York.

EAVIS, B.W. (1972). Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil. Plant and Soil 36, 613-622.

EAVIS, B.W. and PAYNE, D. (1969). Soil physical conditions and root growth. In: Whittington, W.J. (Ed.) Root growth: Proceedings of the 15th Easter School in Agricultural Science, University of Nottingham, 1969, pp. 315-336. London, Butterworths.

EHLERS, W., GRIMME, K., BAEUMER, K., STULPHAGEL, R., KOPKE, U. and BOHM, W. (1981). Flow resistance in soil and plant during field growth of oats. Geoderma 25, 1-12.

EHLERS, W., KOPKE, U., HESSE, F. and BOHM, W. (1983). Penetration resistance and root growth of oats in tilled and untilled loess soil. Soil and Tillage Research 3, 261-275.

EL-KAROURI, M.O.H. and GOODERHAM, P.T. (1977). The effect of soil physical conditions and nitrogen fertilizer on the yield of Italian ryegrass. Journal of Agricultural Science, Cambridge 88, 743-751.

ELSTON, J., KARAMANOS, A.J. and WADSWORTH, R.M. (1978). The water relations of the field bean crop. Philosophical Transactions of the Royal Society of London, B 273, 581-591.

ERIKSSON, J., HÅKANSSON, I. and DANFORS, B. (1974). The effect of soil compaction on soil structure and crop yields. Swedish Institute of Agricultural Engineering, Uppsala, Bulletin 354, p. 101. (English translation by J.K. Aase).

EVANS, C. (1979). Particle size distribution. In: Techniques for measuring soil physical properties. A.D.A.S. Advisory Paper No.18, p. 30. London, HMSO.

EVANS, L.T., WARDLAW, I.F. and FISCHER, R.A. (1975). Wheat. In: Evans, L.T. (Ed.) Crop physiology, pp. 101-150. London, Cambridge University Press.

FARRELL, B.D. and GREACEN, E.L. (1966). Resistance to penetration of fine probes in compressible soil. Australian Journal of Soil Research 4, 1-17.

FASHEUN, A. and DENNET, M.D. (1982). Interception of radiation and growth efficiency in field beans (Vicia faba L.). Agricultural Meteorology 26, 221-229.

FINCH-SAVAGE, W.E. and ELSTON, J. (1976). The death of leaves in crops of field beans. Annals of Applied Biology 85, 463-465.

FINCH-SAVAGE, W.E. and ELSTON, J. (1982). The effect of temperature and water stress on the timing of leaf death in Vicia faba L. Annals of Applied Biology 100, 567-579.

FISHER, J.E. (1964). Evidence of circumnutational growth movements of rhizomes of Poa pratensis L. that aid in soil penetration. Canadian Journal of Botany 42, 293-299.

FISHER, N.M., GOODERHAM, P.T. and INGRAM, J. (1975). The effect on the yields of barley and kale of soil conditions induced by cultivation at high moisture content. Journal of Agricultural Science, Cambridge 85, 385-393.

FLOCKER, W.J., TRIMM, H. and VOMOCIL, J.A. (1960). Effect of soil compaction on tomato and potato yields. Agronomy Journal 52, 345-348.

FOLLET, R.F., SCHMEHL, W.R. and VIETS, Jr. F.G. (1970). Seasonal leaf area, dry weight and sucrose accumulation by sugar beets. Journal of the American Society of Sugar Beet Technology 16 (3), 235-252.

FREE, G.R., LAMB, J. and CARLETON, E.A. (1947). Compactability of certain soils as related to organic matter and erosion. Journal of the American Society of Agronomy 39, 1068-1076.

FRY, G.J. (1975). The physical damage of clay soils and the response of roots. Ph.D. thesis, University of Nottingham.

GALLAGHER, J.N. (1979). Field studies of cereal leaf growth. I. Initiation and expansion in relation to temperature and ontogeny. Journal of Experimental Botany 30, 625-630.

GALLAGHER, J.N., BISCOE, P.V. and SCOTT, R.K. (1976). Barley and its environment. VI. Growth and development in relation to yield. Journal of Applied Ecology 13, 563-583.

GALLAGHER, J.N., BISCOE, P.V., SCOTT, R.K. and RUTH DENNIS-JONES (1977). Barley physiology and its relation to farming practice. In: Yield of cereals, pp. 11-17. Conference Report of the Cereal Demonstration Unit, Stonleigh.

GALLAGHER, J.N. and BISCOE, P.V. (1978). Radiation absorption, growth and yield of cereals. Journal of Agricultural Science, Cambridge 9, 47-60.

GARDNER, W.R. and EHLIG, C.F. (1965). Physical aspects of the internal water relations of plant leaves. Plant Physiology 40, 705-710.

GARWOOD, E.A. and SINCLAIR, J. (1979). Use of water by six grass species. 2. Root distribution and use of soil water. Journal of Agricultural Science, Cambridge 93, 25-35.

GEHRIGER, W. and KELLER, E.R. (1979). Influence de l'écimage sur le developpement de la feverde (Vicia faba L.). Revue Suisse Agric. 11, 215-219. Cited by Peat, W.E. (1983). Developmental physiology. In: Hebblethwaite, P.D. (Ed.) The faba bean (Vicia faba L.), pp. 103-129. London, Butterworths.

GERARD, C.J. (1965). The influence of soil moisture, soil texture, drying conditions and exchangeable cations on soil strength. Soil Science Society of America Proceedings 29, 641-645.

GHADERI, A., SMUCKER, A.J.M. and ADAMS, M.W. (1984). Expected correlated responses in selecting dry beans for tolerance to soil compaction. Euphytica 33, 377-385.

GOESCHL, J.D., RAPPAPORT, L. and PRATT, H.K. (1966). Ethylene as a factor regulating the growth of pea epicotyls subjected to physical stress. Plant Physiology 41, 877-884.

GOODE, J.E. (1956). Soil moisture deficits developed under long and short grass. Annual Report of East Malling Research Station 1955, pp. 64-68.

GOODERHAM, P.T. (1973). Soil physical conditions and plant growth. Ph.D. thesis, University of Reading.

GOODERHAM, P.T. (1976). The effect on soil conditions of mechanical cultivation at high moisture content and of loosening by hand digging. Journal of Agricultural Science, Cambridge 86, 567-571.

GOODERHAM, P.T. (1977). Some aspects of soil compaction, root growth and crop yield. Agricultural Progress 52, 33-42.

GOODERHAM, P.T. and FISHER, N.M. (1975). Experiments to determine the effect of induced soil compaction on soil physical conditions and crop production. In: Soil physical conditions and crop production. Ministry of Agriculture, Fisheries and Food Technical Bulletin 29, pp. 469-480. London, HMSO.

GOSS, M.J. (1974). Effects of mechanical impedance on root growth. Ph.D. thesis, University of Reading.

GOSS, M.J. (1977). Effects of mechanical impedance on root growth in barley (Hordeum vulgare L.). I. Effects on the elongation and branching of seminal root axes. Journal of Experimental Botany 28, 96-111.

GOSS, M.J. and WALTER, C.H.S. (1969). Effect of mechanical resistance on the growth of plant roots. Agricultural Research Council, Letcombe Laboratory Annual Report 1968, pp. 27-28.

GOSS, M.J. and RUSSELL, R.S. (1980). Effects of mechanical impedance on root growth in barley (Hordeum vulgare L.). III. Observations on the mechanisms of the response. Journal of Experimental Botany 31, 577-588.

GRABLE, A.R. (1966). Soil aeration and plant growth. Advances in Agronomy 18, 58-106.

GREACEN, E.L., BARLEY, K.P. and FARRELL, D.A. (1969). The mechanisms of root growth in soils with particular reference to the implications for root distribution. In: Whittington, W.J. (Ed.) Root growth, pp. 256-268. London, Butterworths.

GREACEN, E.L. and OH, J.S. (1972). Physics of root growth. Nature (New Biologist) 235, 24-25.

GREEN, C.F. (1984a). Analysis of wheat growth in relation to husbandry and environment. Ph.D. thesis, University of Nottingham.

GREEN, C.F. (1984b). Discriminants of productivity in small grain cereals : A review. Journal of the National Institute of Agricultural Botany 16, 453-463.

GREEN, C.F. and IVINS, J.D. (1984). Late infestations of take-all (Gaeumannomyces graminis var. tritici) on winter wheat (Triticum aestivum cv. Virtue) : Yield, yield components and photosynthetic potential. Field Crops Research 8, 199-206.

GREENWOOD, D.J. (1969). Effect of oxygen distribution in the soil on plant growth. In: Whittington, W.J. (Ed.) Root growth : Proceedings of the 15th Easter School in Agricultural Science, University of Nottingham, 1969, pp. 202-223. London, Butterworths.

GREGORY, P.J. (1976). The growth and activity of wheat root systems. Ph.D. thesis, University of Nottingham.

GREGORY, P.J., McGOWAN, M. and BISCOE, P.V. (1978). Water relations of winter wheat. 2. Soil water relations. Journal of Agricultural Science, Cambridge 91, 103-116.

GRIMES, D.W., MILLER, R.J. and WILEY, P.L. (1975). Cotton and corn root development in two field soils of different characteristics. Agronomy Journal 67, 519-523.

HANKS, R.J. and THORPE, F.C. (1957). Seedling emergence of wheat, grain sorghum and soybeans as influenced by soil crust strength and moisture content. Soil Science Society of America Proceedings 21, 357-359.

HAWKINS, A.F. (1982). Light interception, photosynthesis and crop productivity. Outlook on Agriculture 2 (3), 104-113.

HEBBLETHWAITE, P.D. (1982). The effects of water stress on the growth, development and yield of Vicia faba L. In: Hawtin, G. and Webb, C. (Eds.) Faba bean improvement. Proceedings of the Faba Bean Conference, The Hague, 1982, pp. 165-175.

HEBBLETHWAITE, P.D. and McGOWAN, M. (1977). Irrigation and nitrogen studies in S23 rye grass grown for seed. 2. Crop transpiration and soil water status. Journal of Agricultural Science, Cambridge 88, 615-624.

HEBBLETHWAITE, P.D. and McGOWAN, M. (1980). The effects of soil compaction on the emergence, growth and yield of sugar beet and peas. Journal of the Science of Food and Agriculture 31, 1131-1142.

HEMSOTH, D.L. and MAZURAK, A.P. (1974). Seedling growth of sorghum in clay sand mixtures at various compactions and water contents. Soil Science Society of America Proceedings 38, 387-390.

HILL-COTTINGHAM, D.G. and TURNER, A.E. (1976). Seasonal variations of enzyme activity in leaves of field bean. Annual Report, Long Ashton Research Station. 1976, p. 47.

HILLEL, D. (1960). Crust formation in Loessial soils. Transactions of the 7th International Congress of Soil Science 1, 330-339.

HODGSON, G.L. and BLACKMAN, G.E. (1957). An analysis of the influence of plant density on the growth of Vicia faba L. II. The significance of competition for light in relation to plant development at different densities. Journal of Experimental Botany 8, 195-219.

HOFFMAN, G.J. and HILER, E.A. (1972). Plant water potential - a new engineering parameter. American Society of Agricultural Engineers, Paper 72-433, St. Joseph, MI 49085.

HOFFMAN, N.E., YANG, S.F. and McKEON, T. (1982). Identification of MACC as a major conjugate of ACC an ethylene precursor in higher plants. Biochemical and Biophysical Research Communications 104, 765-770.

HOLLIDAY, R. (1960). Plant population and crop yield. Parts I and II. Field Crop Abstracts 13 (3), 159-167; and 13 (4), 247-254.

HOUBEN, J.M. (1974). Root development and soil conditions. Bedrijfsontwikkeling 5, 141-148.

HOULDEN, R.W. (1979). The effect of soil compaction on the growth, development and yield of sugar beet. Honours degree dissertation, University of Nottingham.

HSIAO, T.C. and ACEVEDO, E. (1974). Plant responses to water deficits, water use efficiency and drought resistance. Agricultural Meteorology 14, 59-84.

HSIAO, T.C., ACEVEDO, E., FERERES, E. and HENDERSON, D.W. (1976). Water strss, growth and osmotic adjustment. Philosophical transactions of the Royal Society of London, B 273, 479-500.

HUGHES, A.D. (1979). Bulk density. In: Archer, J.R. and Marks, M.J. (Eds.) Techniques for measuring soil physical properties. ADAS Advisory Paper No.18, pp. 38-39. London, HMSO.

HULL, R. and JAGGARD, K.W. (1971). Recent developments in the establishment of sugar beet stands. Field Crop Abstracts 24, (3), 381-390.

HUMPHRIES, E.C. and FRENCH, S.A.W. (1965). A growth study of sugar beet treated with gibberellic acid and (2-chloroethyl) trimethylammonium chloride (CCC). Annals of Applied Biology 55, 159-173.

ISHAG, H.M. (1973). Physiology of seed yield in field beans (Vicia faba L.). I. Yield and yield components. Journal of Agricultural Science, Cambridge 80, 181-189.

ISON, D.A. (1984). Radiation absorption and growth of Vicia faba L. Honours degree dissertation, University of Nottingham.

JACKSON, M.B. (1983). Approaches to relieving aeration stress in waterlogged plants. Pesticide Science 14, 25-32.

JAGGARD, K.W. (1977). Effect of soil density on yield and fertilizer requirements of sugar beet. Annals of Applied Biology 86, 301-312.

JOHNS, G.C. and LAZENBY, A. (1973). Defoliation, leaf area index and the water use of four temperate pasture species under irrigated and dryland conditions. Australian Journal of Agricultural Research 24, 797-808.

JONES, M.M. and TURNER, N.C. (1978). Osmotic adjustment in leaves of sorghum in response to water deficits. Plant Physiology 61, 122-126.

KAMBAL, A.E. (1969). Flower drop and fruit set in field beans. Journal of Agricultural Science, Cambridge 72, 131-138.

KARAMANOS, A.J. (1978). Water stress and leaf growth of field beans (Vicia faba L.) in the field : Leaf number and total leaf area. Annals of Applied Biology 42, 1393-1402.

KAYS, S.J., NICKLOW, C.W. and SIMONS, D.H. (1974). Ethylene in relation to the response of roots to physical impedance. Plant and Soil 40, 565-571.

KEMPER, W.D., STEWART, B.A. and PORTER, L.K. (1971). Effects of compaction on soil nutrient status. In: Barnes, K.K., Carlton, W.M., Taylor, H.M., Throckmorton, R.I. and Vanden Berg, G.E. (Organ Committee). Compaction of Agricultural Soils. American Society of Agricultural Engineers, pp. 178-189. St. Joseph, MI.

KIBREAB, T. (1975). Ph.D. thesis, Colorado State University. Cited by Goss, M.J. and Russell, R.S. (1980). Effects of mechanical impedance on root growth in barley. III. Observations on the mechanism of response. Journal of Experimental Botany 31, 577-588.

KIRBY, E.J.M. (1967). The effect of plant density upon growth and yield of barley. Journal of Agricultural Science, Cambridge 68, 317-324.

KIRBY, E.J.M. and FARIS, D.G. (1970). Plant population induced growth correlations in the barley plant mainstem and possible hormonal mechanism. Journal of Experimental Botany 21, 787-798.

KLEPPER, B. and BARRS, H.D. (1968). Effect of salt secretion on psychrometric determination of water potential of cotton leaves. Plant Physiology 43, 1138-1140.

KRAMER, P.J. (1969). Plant and soil water relationships : a modern synthesis. New York, McGraw-Hill.

KUBOTA, T. and WILLIAMS, R.J.B. (1967). The effects of changes in soil compaction and porosity on germination, establishment and yield of barley and globe beet. Journal of Agricultural Science, Cambridge 68, 227-233.

LACHNO, D.R. (1983). Abscisic acid and indole-3-acetic acid in maize roots subjected to water, salt and mechanical stress. In: Jackson, M.B. and Stead, A.D. (Eds.) Growth regulators in root development, Monograph 10, pp. 37-54. British Plant Growth Regulator Group, Wantage.

LACHNO, D.R., HARRISON-MURRAY, R.S. and AUDUS, L.J. (1982). The effect of mechanical impedance to growth on the levels of ABA and IAA in root tips of Zea mays L. Journal of Experimental Botany 33, 943-951.

LANCASHIRE, B. (1981). An improved method of manufacture for thermopile tube solarimeters. Journal of Agricultural Engineering Research 26, 287-289.

LAWLOR, D.W., DAY, N., JOHNSTON, A.E., LEGG, B.J. and PARKINSON, K.J. (1981). Growth of spring barley under drought : crop development, photosynthesis, dry-matter accumulation and nutrient content. Journal of Agricultural Science, Cambridge 96, 167-186.

LESTER, D.C., CARTER, O.G., KELLEHER, F.M. and LAING, D.R. (1972). The effect of gibberellic acid on apparent photosynthesis and dark respiration of simulated swards of Pennisetum clandestium Hochst. Australian Journal of Agricultural Research 23, 205-213.

LIEBERMAN, M. (1979). Biosynthesis and the action of ethylene. Annual Review of Plant Physiology 30, 533-591.

LINDOO, S.J. and NOODÉN, L.D. (1977). Studies on the behaviour of the senescence signal in Anoka soybeans. Plant Physiology 59, 1136-1140.

LJUNGARS, A. (1977). Olika faktorers betydelse för tractorernas jordpackningsverkan. Mät 1974-1976. (Importance of different factors of soil compaction by tractors. Measurements in 1974-1976.). Agricultural college of Sweden, Department of Soil Science, Division of Soil Management, Report 52 (with English summary).

LOBLEY, P.J. (1982). Interactions between populations and varieties in spring barley. Honours degree dissertation, University of Nottingham.

McEWEN, J. (1982). A little extra expense on inputs could boost bean yields. Arable Farming 4 (9), 53-55.

McGOWAN, M. (1974). Depth of water extraction by roots — Application to soil water balance studies. In: Isotopes and radiation techniques in soil physics and irrigation studies. International Atomic Energy Agency, 1973, pp. 435-445. Vienna.

McGOWAN, M. and WILLIAMS, J.B. (1980). The water balance of an agricultural catchment. I. Estimate of evaporation from soil water records. Journal of Soil Science 31, 217-230.

McGOWAN, M., ARMSTRONG, M.J. and CORRIE, J.A. (1983). A rapid fluorescent-dye technique for measurement of root length. Experimental Agriculture 19, 209-216.

McGOWAN, M., BLANCH, P., GREGORY, P.J. and HAYCOCK, D. (1984). Water relations of winter wheat. 5. The root system and osmotic adjustment in relation to crop evaporation. Journal of Agricultural Science, Cambridge 102, 415-425.

McKIBBEN, E.G. (1971). Introduction. In: Barnes, K.K., Carleton, W.M., Taylor, J.M., Throckmorton, R.I. and Vanden Berg, G.E. (Organ. Comm.). Compaction of Agricultural Soils. American Society of Agricultural Engineers, pp. 3-6. St. Joseph, MI.

McLAREN, J.S. (1981). Field studies on the growth and development of winter wheat. Journal of Agricultural Science, Cambridge 97, 685-697.

MARSHALL, B. and WILLEY, R.W. (1983). Radiation interception and growth in an intercrop of pearl millet/groundnut. Field Crops Research 7, 141-160.

MARKS, M.J. (1979). Strength properties; shear strength. In: Archer, J.R. and Marks, M.J. (Eds.) Techniques for measuring soil physical properties. ADAS Advisory Paper No.18, pp. 51-52. London, HMSO.

MARTIN, R.J. and DOUGHERTY, C.T. (1975). Diurnal variation of water potential of wheat under contrasting weather conditions. New Zealand Journal of Agricultural Research 18, 145-148.

MENGEL, D.B. and BARBER, S.A. (1974). Rate of nutrient uptake per unit of corn root under field conditions. Agronomy Journal 66, 399-402.

MIFORD, G.F.S. (1982). Leaf growth and development. Rothamsted Experimental Station Report 1, pp. 78-79.

MILFORD, G.F.J. and RILEY, J. (1980). The effects of temperature on leaf growth of sugar beet varieties. Annals of Applied Biology 94, 431-443.

MILFORD, G.F.J., POCOCK, T.O., JANET RILEY and MESSEM, A.B. (1985). An analysis of leaf growth in sugar beet. III. Leaf expansion in field crops. Annals of Applied Biology 106, 187-203.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (1967). Potential transpiration. Technical Bulletin No.16, Ministry of Agriculture, Fisheries and Food. London, HMSO.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (1973). The analysis of agricultural materials. Technical Bulletin 27. London, HMSO.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (1979a). Determination of the moisture retention properties of soil using a sand tension table. In: Archer, J.R. and Marks, M.J. (Eds.) Techniques for measuring soil physical properties. ADAS Advisory Paper No.18, p. 62. London, HMSO.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (1979b). Determination of the moisture retention properties of soil using the pressure membrane unit. In: Archer, J.R. and Marks, M.J. (Eds.) Techniques for measuring soil physical properties. ADAS Advisory Paper No.18, p. 64. London, HMSO.

MINISTRY OF AGRICULTURE, FISHERIES AND FOOD (1983). Annual review of agriculture. London, HMSO.

MIRREH, H.F. and KETCHESON, J.W. (1972). Influence of soil bulk density and matric pressure on soil resistance to penetration. Canadian Journal of Soil Science 52, 477-483.

MONTEITH, J.L. (1959). Solarimeter for field use. Journal of Scientific Instruments 36, 341-346.

MONTEITH, J.L. (1977). Climate and the efficiency of crop production in Britain. Philosophical Transactions of the Royal Society of London, B 281, 277-294.

MONTEITH, J.L. (1981). Does light limit crop production? In: Johnson, C.B. (Ed.) Physiological processes limiting plant productivity, pp. 23-38. London, Butterworths.

MONTEITH, J.L. and ELSTON, J. (1983). Performance and productivity of foliage in the field. In: Dale, J.E. and Milthorpe, F.C. (Eds.) The growth and functioning of leaves, pp. 499-518. London, Cambridge University Press.

MORTON, A.G. and WATSON, D.J. (1948). A physiological study of leaf growth. Annals of Botany 47, 281-310.

MUSICK, J.T., DUSEK, D.A. and SCHNEIDER, A.D. (1981). Deep tillage of an irrigated Pullman clay loam - a long term evaluation. Transactions of the American Society of Agricultural Engineers 24, 1515-1519.

NEWMAN, E.I. (1966). A method for estimating the total length of roots in a sample. Journal of Applied Ecology 11, 309-314.

O'SULLIVAN, M.F. and BALL, B.C. (1982a). A comparison of five instruments for measuring soil strength in cultivated and uncultivated cereal seedbeds. Journal of Soil Science 33, 597-608.

O'SULLIVAN, M.F. and BALL, B.C. (1982b). Spring barley growth, grain quality and soil physical conditions in a cultivation experiment on a sandy loam in Scotland. Soil Tillage Research 2, 359-378.

O'TOOLE, J.C. (1981). Response of rice root systems to simulated soil compaction with emphasis on water uptake (Abstract). American Society of Agronomy 73rd Annual Meeting, p. 93.

OSBORNE, D.J. (1976). Control of cell shape and cell size by the dual regulation of auxin and ethylene. Perspectives in Experimental Biology, Volume 2, 89-102.

PAYNE, P.C.J. and FOUNTAINE, E.R. (1952). A field method of measuring the shear strength of soils. Journal of Soil Science 3, 136-144.

PEAT, W.E. (1983). Developmental physiology. In: Hebblethwaite, P.D. (Ed.) The faba bean (Vicia faba L.), pp. 103-129. London, Butterworths.

PERCIVAL, J. (1921). The wheat plant. London, Duckworth and Company.

PERRY, D.A. (1973). Studies on field establishment of monogerm sugar beet. Journal of Agricultural Science, Cambridge 81, 245-252.

PETERSON, W.R. and BARBER, S.A. (1981). Soybean root morphology and K-uptake. Agronomy Journal 73, 316-319.

PHILLIPS, R.E. and KIRKHAM, D. (1962). Soil compaction in the field corn crop. Agronomy Journal 54, 29-34.

PIDGEON, J.D. (1980). An experimental study of the suitability of two soils for direct drilling of spring barley. Journal of Soil Science 31, 581-594.

PIDGEON, J.D. and SOANE, B.D. (1977). Effects of tillage and direct drilling on soil properties during the growing season in a long-term barley mono-culture system. Journal of Agricultural Science, Cambridge 88, 431-442.

PIDGEON, J.D. and SOANE, B.D. (1978). Soil structure and strength relations following tillage, zero-tillage and wheel traffic in Scotland. In: Emerson, W.W., Bond, R.D. and Dexter, A.R. (Eds.) Modification of soil structure, pp. 371-379. Chichester, John Wiley.

PRIHAR, S.S. and CHOWDHARY, M.R. (1977). Crop response to soil compaction, seedling emergence and root growth. In: Gupta, U.S. (Ed.) Physiological aspects of soil nutrition and resistance. pp. 289-310.

PROCTOR, R.R. (1933). Fundamental principles of soil compaction. Engineering News Record 111, 245-248.

PUCKERIDGE, D.W. and DONALD, C.M. (1967). Competition among wheat plants sown at a wide range of densities. Australian Journal of Agricultural Research 18, 193-211.

RAWSON, H.M. and DONALD, C.M. (1969). The absorption and distribution of nitrogen after floret initiation in wheat. Australian Journal of Agricultural Research 20, 799-808.

RICHARDS, L. (1953). Modulus of rupture as an index of crusting of soil. Soil Science Society of America Proceedings 17, 321-323.

RICHARDS, D.F., GAUBRAN, J.H., GARWOLI, W.N. and DOLY, M.W. (1979). A method for determining root length. Plant and Soil 52, 69-76.

RITCHIE, G.A. and HINCKLEY, T.M. (1975). The pressure chamber as an instrument for ecological research. Advances in Ecological Research 9, 165-254.

ROWSE, H.R. and PHILLIPS, D.A. (1974). An instrument for estimating the total length of root in a sample. Journal of Applied Ecology 11, 309-314.

ROWSE, H.R. and STONE, D.A. (1981). Deep cultivation of a sandy clay loam. II. Effects on soil hydraulic properties and on root growth, water extraction and water stress in 1977 especially of broad beans. Soil and Tillage Research 1, 173-185.

ROYLE, S.M. (1973). Methods of studying soil capping. Honours degree dissertation, University of Nottingham.

RUSSELL, E.W. (1971). Soil structure : its maintenance and improvement. Journal of Soil Science 22, 137-151.

RUSSELL, E.W. (1973). Soil conditions and plant growth. 10th edition, Longmans.

RUSSELL, R.S. (1968). The form of root systems. Agricultural Research Council, Letcombe Laboratory Annual Report 1968, pp. 3-5.

RUSSELL, R.S. and GOSS, M.J. (1974). Physical aspects of soil fertility - The response of roots to mechanical impedance. Netherlands Journal of Agricultural Science 22, 305-318.

SAFFELL, R.A., CAMPBELL, G.S. and CAMPBELL, E.C. (1979). An improved micropower counting integrator. Agricultural Meteorology 20, 393-396.

SAMIMY, C. (1980). Possible involvement of ethylene in differential growth responses of hypocotyls of two soybean cultivars to physical impediment. Journal of Seed Technology 5, 74-81.

SCHUMACHER, T.E. and SMUCKER, A.J.M. (1981). Mechanical impedance effects on oxygen uptake and porosity of drybean roots. Agronomy Journal 73, 51-55.

SCHUURMAN, J.J. (1965). Influence of soil density on root development and growth of oats. Plant and Soil 22, 352-374.

SCOTT, R.K., ENGLISH, S.D., WOOD, D.W. and UNSWORTH, M.H. (1973). The yield of sugar beet in relation to weather and length of growing season. Journal of Agricultural Science, Cambridge 81, 339-347.

SCOTT, R.K. and JAGGARD, K.W. (1978). How the crop grows - from seed to sugar. British Sugar Beet Review 46 (4), 19-22.

SHIBLES, R.M. and WEBER, C.R. (1965). Leaf area, solar radiation and dry matter production by soybeans. Crop Science 5, 575-577.

SIBMA, L. (1970). Relation between total radiation and yield of some field crops in the Netherlands. Netherlands Journal of Agricultural Science 18, 125-131.

SIBMA, L. (1977). Maximization of arable crop yields in the Netherlands. Netherlands Journal of Agricultural Science 25, 278-287.

SOANE, B.D. (1970). The effects of traffic and implements on soil compaction. Journal of the Proceedings of the Institute of Agricultural Engineers 25, 115-126.

SOANE, B.D. (1975). Studies on some soil physical properties in relation to cultivations and traffic. In: Soil physical conditions and crop production. Ministry of Agriculture, Fisheries and Food Technical Bulletin 29, pp. 160-183. London, HMSO.

SOANE, B.D. (1981). Compaction by vehicles : Problems and opportunities. In: Soil compaction "causes and cures". Proceedings of the Soil and Water Management Association Conference, Silsoe, Bedfordshire, 1981, Paper 2.

SOANE, B.D., DICKSON, J.W. and BLACKWELL, P.S. (1979). Some options for reducing compaction under wheels on loose soil. Proceedings of the 8th Conference of the International Soil Tillage Research Organisation, Stuttgart 2, pp. 347-352.

SOANE, B.D., BLACKWELL, P.S., DICKSON, J.W. and PAINTER, D.J. (1981). Compaction of agricultural vehicles : A review. I. Soil and wheel characteristics. Soil and Tillage Research 1, 207-237.

SOANE, B.D., DICKSON, J.W. and CAMPBELL, D.J. (1982). Compaction by agricultural vehicles : A review. III. Incidence and control of compaction in crop production. Soil and Tillage Research 2, 3-36.

STEVEN, M.D. (1977). Angular distribution and interception of diffuse solar radiation. Ph.D. thesis, University of Nottingham.

STEVENS, M.D., BISCOE, P.V., JAGGARD, K.W. and PARUNTU, J. (1985). Foliage cover and radiation interception. Journal of Experimental Botany (In Press).

STOLZY, L.H. and BARLEY, K.P. (1968). Mechanical resistance encountered by roots entering compact soils. Soil Science 105, 297-301.

SUGAR BEET RESEARCH AND EDUCATION COMMITTEE (1982a). Sugar beet - a grower's guide. 2nd edition, Higham, Sugar Beet Research and Education Committee.

SUGAR BEET RESEARCH AND EDUCATION COMMITTEE (1982b). Physiology of growth of the sugar beet crop. Committee Paper number 1911. Higham, Sugar Beet Research and Education Committee.

SWAIN, R.W. (1981). The field problem - compaction and yield. In: Soil Compaction "causes and cures": Proceedings of the Soil and Water Management Association Conference, Silsoe, Bedfordshire, 1981, Paper 1.

SZEICZ, G. (1974). Solar radiation in crop canopies. Journal of Applied Ecology 11, 1117-1156.

SZEICZ, G., MONTEITH, J.L. and DOS SANTOS, J.M. (1964). Tube solarimeter to measure radiation among plants. Journal of Applied Ecology 1, 169-174.

TAYLOR, H.M. (1971). Effects of soil strength on seedling emergence, root growth and crop yield. In: Barnes, K.K., Carlton, W.M., Taylor, H.M., Throckmorton, R.I. and Vanden Berg, G.E. (Organ. Comm.). Compaction of Agricultural Soils. American Society of Agricultural Engineers, pp. 292-305. St. Joseph, MI.

TAYLOR, S.A. and SLATYER, R.O. (1961). Proposals for a unified terminology in studies of plant-soil-water relationships. UNESCO Arid Zone Research 16, 339-343.

TAYLOR, H.M. and BURNETT, E. (1964). Influence of soil strength on the root growth habits of plants. Soil Science 98, 174-180.

TAYLOR, H.M., ROBERSON, G.M. and PARKER, J.J. (1966). Soil strength - root penetration relations for medium - to coarse - textured soil materials. Soil Science 102, 18-22.

TAYLOR, H.M. and RATCLIFF, L.F. (1969). Root elongation rates of cotton and peanuts as a function of soil strength and soil water content. Soil Science 108, 113-119.

TAYLOR, H.M. and KLEPPER, B. (1978). The role of rooting characteristics in the supply of water to plants. Advances in Agronomy 30, 99-128.

THOMAS, H. and STODDART, J.L. (1980). Leaf senescence. Annual Review of Plant Physiology 31, 83-111.

THOMASSON, A.J. (1971). Soils of the Melton Mowbray district. Memorandum of the Soil Survey of Great Britain. London, HMSO.

THOMPSON, R. and TAYLOR, H. (1977). Yield components and cultivar sowing date and density in field beans (Vicia faba). Annals of Applied Biology 86, 313-320.

THOMPSON, R. and TAYLOR, H. (1981). Factors limiting growth and yield of Vicia faba. In: Thompson, R. (Ed.) Vicia faba : Physiology and breeding. Proceedings of the EEC Seminar, Wageningen, 1981, pp. 34-35. Martinus Nijhoff and Commission of European Communities.

THOMPSON, R. and TAYLOR, H. (1982). Prospects for Vicia faba L. in Northern Europe. Outlook on Agriculture 11, 127-133.

THORNE, G.N. (1962). Survival of tillers and distribution of dry matter between ear and shoot in barley varieties. Annals of Botany 26, 37-54.

THORNE, G.N. (1981). Growth and development of cereals and the environment. In: Hawkins, A. and Jeffcoat, B. (Eds.) Opportunities for Manipulating Cereal Productivity, Monograph 7, pp. 204-209. British Plant Growth Regulator Group, Wantage.

TOWNSEND, C.E. (1972). Influence of seed size and depth of planting on seedling emergence of two Milkvetch species. Agronomy Journal 64, 627-630.

TROUSE, A.C. (1966). Alteration of the infiltration permeability capacity of tropical soils by vehicular traffic. 1st Pan-American Soil Conservation Congress, Sao Paulo, Brazil, pp. 1103-1109. Cited by Soane, B.D., Blackwell, P.S., Dickson, J.W. and Painter, D.J. (1981). Compaction by agricultural vehicles : a review. I. Soil and wheel characteristics. Soil and Tillage Research 1, 207-237.

TROUSE, A.C. (1971). Effect of soil moisture on plant activities. In: Barnes, K.K., Carlton, W.M., Taylor, H.M., Throckmorton, R.I. and Vanden Berg, G.E. (Organ. Comm.). Compaction of agricultural soils. American Society of Agricultural Engineers, pp. 241-253. St. Joseph, MI.

TROUSE, A.C. and HUMBERT, R.P. (1961). Some effects of soil compaction on the development of sugar cane roots. Soil Science 91, 208-217.

TURNER, N.C. (1974). Stomatal responses to light and water under field conditions. In: Mechanisms of regulation of plant growth, pp. 423-432. New Zealand, Royal Society.

TURNER, N.C., DEROO, H.C. and WRIGHT, W.M. (1971). A pressure chamber for the measurement of plant water potential. Connecticut Agricultural Experimental Station, Soils Bulletin 33, p. 9.

VAN BAVEL, C.H.M. and STIRK, G.B. (1967). Soil water measurements with a 241 Am-Be neutron source and an application to evapormetry. Journal of Hydrology 5, 40-46.

VIRGIL (70-19 BC). Cited by Tisdale, S.L. and Nelson, W.W. (1966). Soil fertility and fertilizers, p. 9. New York, Macmillian.

VISUALINGHAM, M. and TANDY, J.D. (1972). The neutron method for measuring soil moisture content - A review. Journal of Soil Science 23 (4), 227-239.

VOORHEES, W.B. (1977). Soil compaction : Our newest natural resource. Crops and Soils Magazine 29, 13-15.

VOORHEES, W.B. (1983). Relative effectiveness of tillage and natural forces in alleviating wheel-induced soil compaction. Soil Science Society of America Journal 47, 129-133.

VOORHEES, W.B., SENST, C.G. and NELSON, W.W. (1978). Compaction and soil modification by wheel traffic in the Northern Corn Belt. Soil Science Society of America Journal 42, 344-349.

WALLACE, J.S. (1978). Water transport and leaf water relations in winter wheat crops. Ph.D. thesis, University of Nottingham.

WANG, T.L. and WOOLHOUSE, H.W. (1982). Hormonal aspects of senescence in plant development. In: Jackson, M.B., Grout, B. and Mackenzie, I.A. (Eds.) Growth regulators in plant senescence, Monograph 8, pp. 5-25. British Plant Growth Regulator Group, Wantage.

WARD, T.M., WRIGHT, M., ROBERTS, J.A., SELF, R. and OSBORNE, D.J. (1978). Analytical procedures for the assay and identification of ethylene. In: Hillman, J.R. (Ed.) Isolation of plant growth substances. Society for Experimental Biology Seminar Series 4, pp. 135-151. Cambridge, Cambridge University Press.

WAREING, P.F. and PHILLIPS, I.D.J. (1970). The control of growth and differentiation in plants, pp. 255-257. Oxford, Pergamon Press.

WATERER, R.R. (1981). The production of the field bean (Vicia faba L.). Honours degree dissertation, University of Nottingham.

WEAVER, J.E. and HIMMEL, W.J. (1930). Relation of increased water content and decreased aeration to root development of hydrophytes. Plant Physiology 5, 69-92.

WEBSTER, R. (1966). Measurements of soil water tension in the field. New Phytologist 65, 249-258.

WELBANK, P.J., GIBB, M.J., TAYLOR, P.J. and WILLIAMS, E.D. (1972). Root growth of cereal crops. Rothamsted Annual Report 1971 2, pp. 26-66.

WHITELEY, G.M., UTOMO, W.H. and DEXTER, A.R. (1981). A comparison of penetrometer pressures and the pressures exerted by roots. Plant and Soil 61, 351-364.

WIEBE, H.H. (1966). Matric potential of several plant tissues and biocolloids. Plant Physiology 41, 1439-1442.

WIERSUM, L.K. (1957). The relationship of the size and structural rigidity of pores to their penetration by roots. Plant and Soil 9, 75-85.

WILDHOLM, J.M. (1979). The use of fluorescein diacetate and pheno safranine for determining viability of cultured plant cells. Stain Technology 47, 189-194.

WILKINS, H., LARQUE-SAAVEDRA, A. and WAIN, R.L. (1974). Studies on plant growth-regulating substances. XXXVII. The effects of light and hormone inhibitors on plant root growth. Annals of Applied Biology 78, 169-177.

WILKINS, H., WILKINS, S.M. and WAIN, R.L. (1977). Studies on plant growth regulating substances. XLVIII. The effects of 3,5, diiodo-4-hydroxybenzoic acid on seedling growth in compacted and loose soils. Annals of Applied Biology 87, 415-422.

WILKINSON, B. (1975). Field experiments on heavy soils. In: Soil physical conditions and crop production. Ministry of Agriculture, Fisheries and Food Technical Bulletin 29, pp. 76-94. London, HMSO.

WILLIAMS, J.B. (1971). The water balance of an agricultural catchment. Ph.D. thesis, University of Nottingham.

WILLIAMS, J. and SHAYKEWICH, C.F. (1970). The influence of soil water matric potential on the strength properties of unsaturated soil. Soil Science Society of America Proceedings 34, 835-839.

WILSON, A.J., ROBARDS, A.W. and GOSS, M.J. (1977). Effects of mechanical impedance on root growth in barley, Hordeum vulgare L. II. Effects on cell development in seminal roots. Journal of Experimental Botany 28, 1216-1227.

WILSON, A.J. and ROBARDS, A.W. (1979). Some observations of the effects of mechanical impedance upon the ultrastructure of the root caps of barley (Hordeum vulgare cv. Proctor). Protoplasma 101, 61-72.

WIND, G.P. (1955). Flow of water through plant roots. Netherlands Journal of Agricultural Science 3, 259-264.

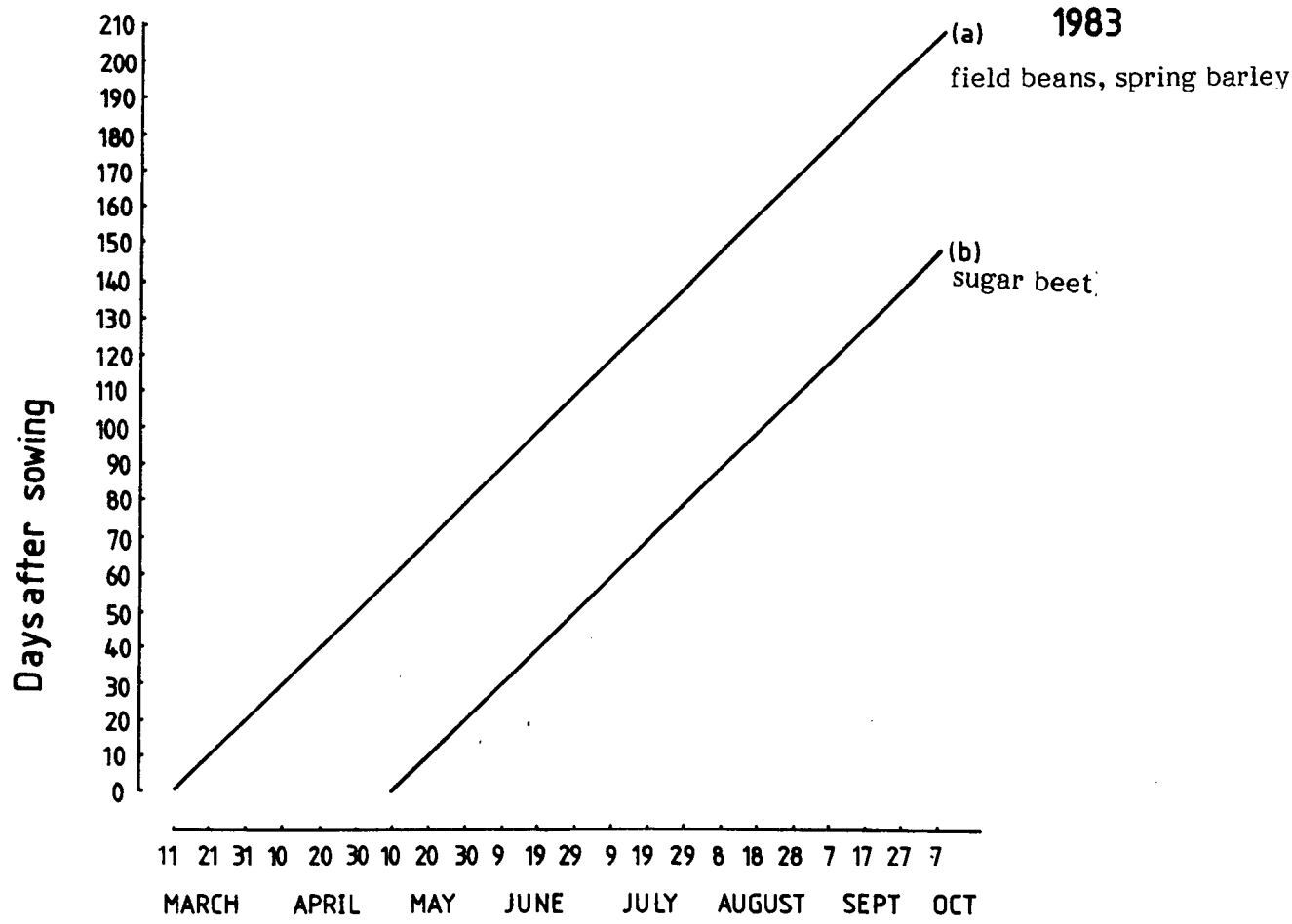
WOLF, F.T. and HABER, A.M. (1960). Chlorophyll content of gibberellin-treated wheat seedlings. Nature, London 186, 217-218.

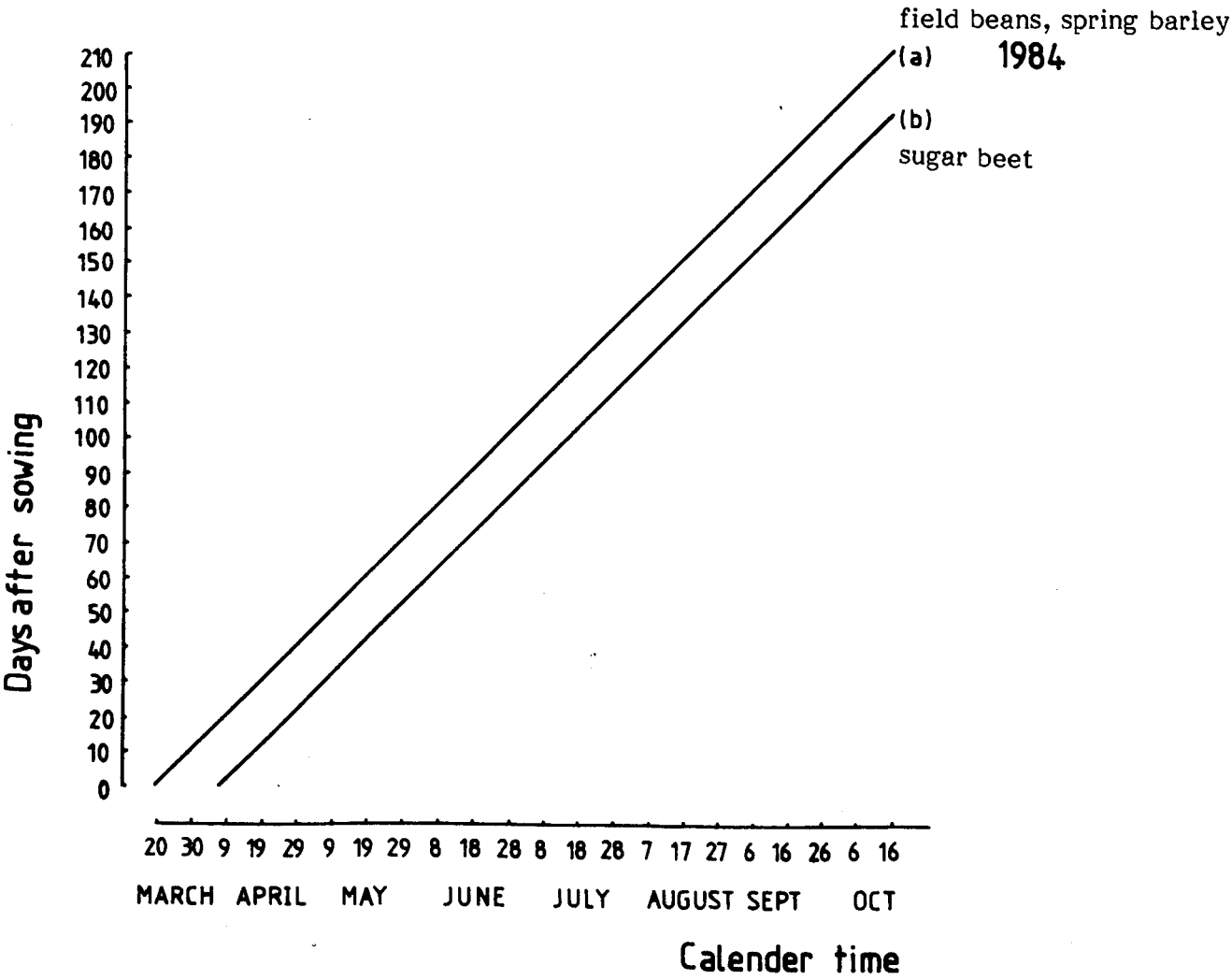
WORMINGTON, C.A.H. (1984). Soil water relations of faba bean (Vicia faba L.). Plant Models. Honours degree dissertation, University of Nottingham.

YOUNG, R.E. and BROWNING, V.D. (1977). Cotton leaf water potential and yields relative to tillage and traffic. Transactions of the American Society of Agricultural Engineers 20, 673-682.

APPENDICES

Appendix 1 The relationship between days after sowing and calendar time for field beans, spring barley and sugar beet in 1983 and 1984


1983
(a)
field beans, spring barley
(b)
sugar beet
Days after sowing
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
11 21 31 10 20 30 10 20 30 9 19 29 9 19 29 8 18 28 7 17 27 7
MARCH APRIL MAY JUNE JULY AUGUST SEPT OCT


field beans, spring barley
(a)
1984
(b)
sugar beet
Days after sowing
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
20 30 9 19 29 9 19 29 8 18 28 8 18 28 7 17 27 6 16 26 6 16
MARCH APRIL MAY JUNE JULY AUGUST SEPT OCT
Calender time

Appendix 2 Statistical analysis of crop emergence data given in Figure 4.1

Days after sowing	Plant numbers per metre length			
	Control	Compact	SED	Sig* (3DF)
Field beans				
31	3.75	0.25	1.27	NS
33	6.25	0.50	1.78	NS
35	7.00	1.25	2.02	NS
36	7.50	1.25	1.93	NS
38	7.50	2.50	2.07	NS
40	7.50	2.75	2.06	NS
Spring barley				
22	13.00	0.25	1.95	$p<0.01$
23	19.25	1.00	1.47	$p<0.01$
27	30.50	7.50	3.91	$p<0.05$
28	32.70	12.30	3.85	$p<0.05$
29	34.00	13.50	4.26	$p<0.05$
31	34.00	17.00	3.11	$p<0.01$
33	34.70	18.00	3.43	$p<0.05$
35	34.70	18.20	3.44	$p<0.05$
36	35.70	18.70	3.00	$p<0.01$
38	35.70	18.70	3.00	$p<0.01$
Sugar beet	Plant numbers per 3 metre length			
16	7.75	0.10	1.64	$p<0.01$
18	16.50	3.00	1.71	$p<0.01$
19	17.50	4.75	1.80	$p<0.01$
21	18.25	5.50	1.49	$p<0.01$
24	18.50	5.75	1.49	$p<0.01$
29	18.75	5.75	1.47	$p<0.01$
36	19.00	5.75	1.44	$p<0.01$
44	19.25	5.75	1.44	$p<0.01$

* level of statistical significance

Appendix 3 Statistical Analysis for sugar beet dry weight data presented in text

Table 1 Statistical analysis for sugar beet dry weight data given in Figure 4.9

Days after sowing	Plant organ	Dry weight (gm^{-2}) Control	Compact	SED	Sig* (3DF)
64	leaf + petiole	87.7	10.8	13.9	$p<0.01$
	crown + root	61.9	4.4	18.4	NS
77	leaf + petiole	231.0	34.0	45.0	$p<0.05$
	crown + root	234.0	20.0	22.9	$p<0.01$
100	leaf	265.0	90.0	26.7	$p<0.001$
	petiole	137.3	47.1	21.3	$p<0.01$
	crown	96.1	44.5	15.2	$p<0.05$
	root	516.0	167.0	77.1	$p<0.01$
120	leaf	444.0	216.0	71.7	$p<0.05$
	petiole	248.0	99.0	49.5	$p<0.05$
	crown	350.0	160.0	48.0	$p<0.01$
	root	1175.0	521.0	214.7	$p<0.05$
140	leaf	503.0	312.0	36.4	$p<0.01$
	petiole	298.0	158.0	30.6	$p<0.01$
	crown	392.0	218.0	40.3	$p<0.01$
	root	1937.0	745.0	106.3	$p<0.001$

* level of statistical significance

Table 2 Statistical analysis for sugar beet dry weight data given in Figure 4.10

Days after sowing	Plant organ	Dry weight (g plant^{-1}) Control	Compact	SED	Sig* (3DF)
64	leaf + petiole	6.8	1.3	0.8	$p<0.01$
	crown + root	4.7	0.5	1.3	$p<0.05$
77	leaf + petiole	18.4	4.2	4.3	$p<0.05$
	crown + root	18.6	2.5	2.4	$p<0.01$
100	leaf	20.8	10.9	2.6	$p<0.05$
	petiole	10.7	5.9	2.0	NS
	crown	7.5	5.5	1.6	NS
	root	40.5	20.9	7.5	NS
120	leaf	35.1	26.8	8.8	NS
	petiole	19.6	12.2	5.8	NS
	crown	27.8	19.7	5.7	NS
	root	93.0	65.0	25.9	NS
140	leaf	39.4	37.2	4.2	NS
	petiole	23.3	18.5	3.1	NS
	crown	30.7	25.9	5.2	NS
	root	151.9	88.2	13.9	$p<0.01$

* level of statistical significance

Table 3 Statistical analysis for sugar beet dry weight data given in Figure 4.11

Days after sowing	Plant organ	Dry weight (gm^{-2}) Control	Compact	SED	Sig* (3DF)
67	leaf	58.8	10.9	3.4	$p<0.001$
	petiole	14.9	2.5	0.9	$p<0.01$
	crown	11.2	2.2	0.2	$p<0.001$
	root	16.5	2.7	1.0	$p<0.001$
75	leaf	147.2	29.0	11.6	$p<0.01$
	petiole	64.0	9.2	3.9	$p<0.001$
	crown	44.1	7.2	4.7	$p<0.01$
	root	90.0	13.6	7.2	$p<0.001$
82	leaf	163.1	51.4	3.5	$p<0.001$
	petiole	86.0	20.8	3.6	$p<0.001$
	crown	55.0	12.1	5.9	$p<0.01$
	root	122.5	31.6	9.3	$p<0.01$
89	leaf	208.0	69.0	23.3	$p<0.01$
	petiole	129.5	35.7	17.3	$p<0.01$
	crown	72.7	23.2	11.4	$p<0.05$
	root	185.0	59.0	59.9	NS
108	leaf	330.0	151.0	26.1	$p<0.01$
	petiole	327.0	105.0	35.7	$p<0.01$
	crown	125.1	58.4	7.6	$p<0.001$
	root	748.0	380.0	37.2	$p<0.001$
130	leaf	328.7	177.1	19.9	$p<0.01$
	petiole	304.6	127.4	19.7	$p<0.001$
	crown	119.0	47.0	21.3	$p<0.05$
	root	1221.0	601.0	102.9	$p<0.01$
150	leaf	356.0	257.0	24.9	$p<0.05$
	petiole	290.0	174.0	37.2	$p<0.05$
	crown	178.0	98.0	33.0	NS
	root	1846.0	1392.0	157.1	$p<0.05$
166	leaf	314.0	266.0	42.6	NS
	petiole	275.0	154.0	29.6	$p<0.05$
	crown	270.0	184.5	16.5	$p<0.01$
	root	2047.0	1445.0	136.9	$p<0.05$

* level of statistical significance

Table 4 Statistical analysis for sugar beet dry weight data given in Figure 4.12

Days after sowing	Plant organ	Dry weight (g plant^{-1}) Control	Compact	SED	Sig* (3DF)
67	leaf	4.74	2.47	0.09	$p<0.001$
	petiole	1.20	0.58	0.08	$p<0.01$
	crown	0.91	0.51	0.09	$p<0.05$
	root	1.33	0.60	0.05	$p<0.001$
75	leaf	11.94	6.58	1.20	$p<0.05$
	petiole	5.19	2.09	0.38	$p<0.01$
	crown	3.58	1.62	0.45	$p<0.05$
	root	7.28	3.06	0.62	$p<0.01$
82	leaf	13.23	11.50	0.39	$p<0.05$
	petiole	6.96	4.68	0.26	$p<0.01$
	crown	4.45	2.68	0.81	NS
	root	9.90	6.99	0.62	$p<0.05$
89	leaf	16.90	15.40	2.11	NS
	petiole	10.48	7.97	1.74	NS
	crown	5.91	5.17	1.22	NS
	root	14.90	13.10	5.12	NS
108	leaf	26.70	33.70	2.17	$p<0.05$
	petiole	26.60	23.40	3.00	NS
	crown	10.18	12.93	1.28	NS
	root	60.50	75.00	4.80	$p<0.05$
130	leaf	26.75	39.78	1.35	$p<0.001$
	petiole	24.80	28.80	2.03	NS
	crown	9.70	10.70	1.35	NS
	root	99.10	135.60	7.26	$p<0.01$
150	leaf	29.00	59.10	7.03	$p<0.05$
	petiole	23.60	39.60	4.81	$p<0.05$
	crown	14.50	22.20	2.66	$p<0.05$
	root	150.00	318.00	36.20	$p<0.01$
166	leaf	25.60	59.50	21.70	$p<0.01$
	petiole	22.30	34.60	2.04	$p<0.01$
	crown	22.00	41.40	5.63	$p<0.05$
	root	167.00	324.00	4.37	$p<0.01$

* level of statistical significance

APPENDIX 4

Equations used in the calculation of fractional light interception and absorption of radiation by crop canopies

The fraction of solar radiation intercepted by the crop (F_i) can be calculated from the transmitted fraction (T_t) by the equation:

$$F_i = 1 - T_t \qquad \text{(A.1)}$$

Solarimeter measurements of the light interception of the compact sugar beet treatment produced highly variable data as a result of the low plant density and patchy crop, thus the light interception of the compact treatment was estimated from the LAI of the canopy (L) using the equation:

$$F_i = 1 - \exp(-KL) \qquad \text{(A.2)}$$

(Monteith, 1981)

where K is the attenuation coefficient of the sugar beet leaf canopy, calculated from measurements of fractional foliage cover (F_g) which were determined using the photographic technique during early linear growth (see equation A.3).

$$K = -\ln(1 - F_g)/L \qquad \text{(A.3)}$$

K was assumed to be constant throughout the period of measurement.

Tube solarimeters can measure the fraction of total radiation transmitted through the canopy (T_t) but since PAR is selectively absorbed

by green foliage, the following power law expression was used to calculate T_p from T_t:

$$T_p = T_t^{1.4} \tag{A.4}$$

(Marshall and Willey, 1983)

The fraction of Photosynthetically Active Radiation (PAR) absorbed (F_p) by a crop cannot be measured directly but can be estimated from the fraction of PAR transmitted (T_p) and reflected (R_p) by using the equation:

$$F_p = 1 - T_p - R_p \tag{A.5}$$

(Gallagher and Biscoe, 1978)

The reflection of radiation from the leaf canopy is a constant fraction of the incident radiation and is usually less than 10% of the absorbed PAR (Monteith, 1981) such that:

$$R_p = 0.1\, F_p \tag{A.6}$$

it now follows

$$F_p = (1 - T_t^{1.4})/1.11 \tag{A.7}$$

(Gallagher and Biscoe, 1978)

The PAR absorbed daily by the crop canopy was determined from the product of the fraction of PAR absorbed and the total PAR incident on the crop; assumed to be equal to half the total solar radiation (S_t),

$$PAR_{abs} = F_p\,(S_{t/2}) \tag{A.8}$$

(Szeicz, 1974)

APPENDIX 5

Light interception determined from measurements of foliage cover

Stevens, Biscoe, Jaggard and Paruntu (1985) found that an estimate of the fraction of light intercepted (F_e) by a crop could be made from photographic measurements of fractional foliage cover (F_f) by using the equation:

$$F_e = 1 - (1 - F_g)^{K_i/K_f} \qquad (A.9)$$

where K_i and K_f are the attenuation coefficients of the leaf canopy derived from solarimeter measurements of light interception (F_i) and from photographic measurements (F_f) of fractional foliage cover, respectively.

Stevens et al. (1985) found that for field bean and sugar beet crops, F_f gave an adequate estimate of F_i since these crops had large leaves with a lax canopy. However, difficulties of obtaining an accurate estimate of the ground cover of spring barley with small, erect leaves resulted in a poor correlation between F_f and F_i. The fraction of light intercepted by barley crops was estimated from measurements of F_f (Table A.1) using equation A.9.

Table A.1 Photographic measurements of fractional foliage cover

Days after sowing	Fractional foliage cover (F_f)			
	Control	Compact	SED	Sig (3DF)*
36	0.29	0.13	0.01	$p<0.01$
43	0.44	0.19	0.02	$p<0.001$
52	0.76	0.29	0.02	$p<0.001$
59	0.86	0.37	0.03	$p<0.001$
65	0.88	0.83	0.02	NS
79	0.92	0.82	0.04	NS

* level of statistical significance

The attenuation coefficients of radiation for the barley leaf canopy were determined from the photographic measurements of F_f using equation:

$$K_f = -\ln(1 - F_f)/L \qquad (A.10)$$

and from F_i using the equation:

$$K_i = -\ln(1 - F_i)/L \qquad (A.11)$$

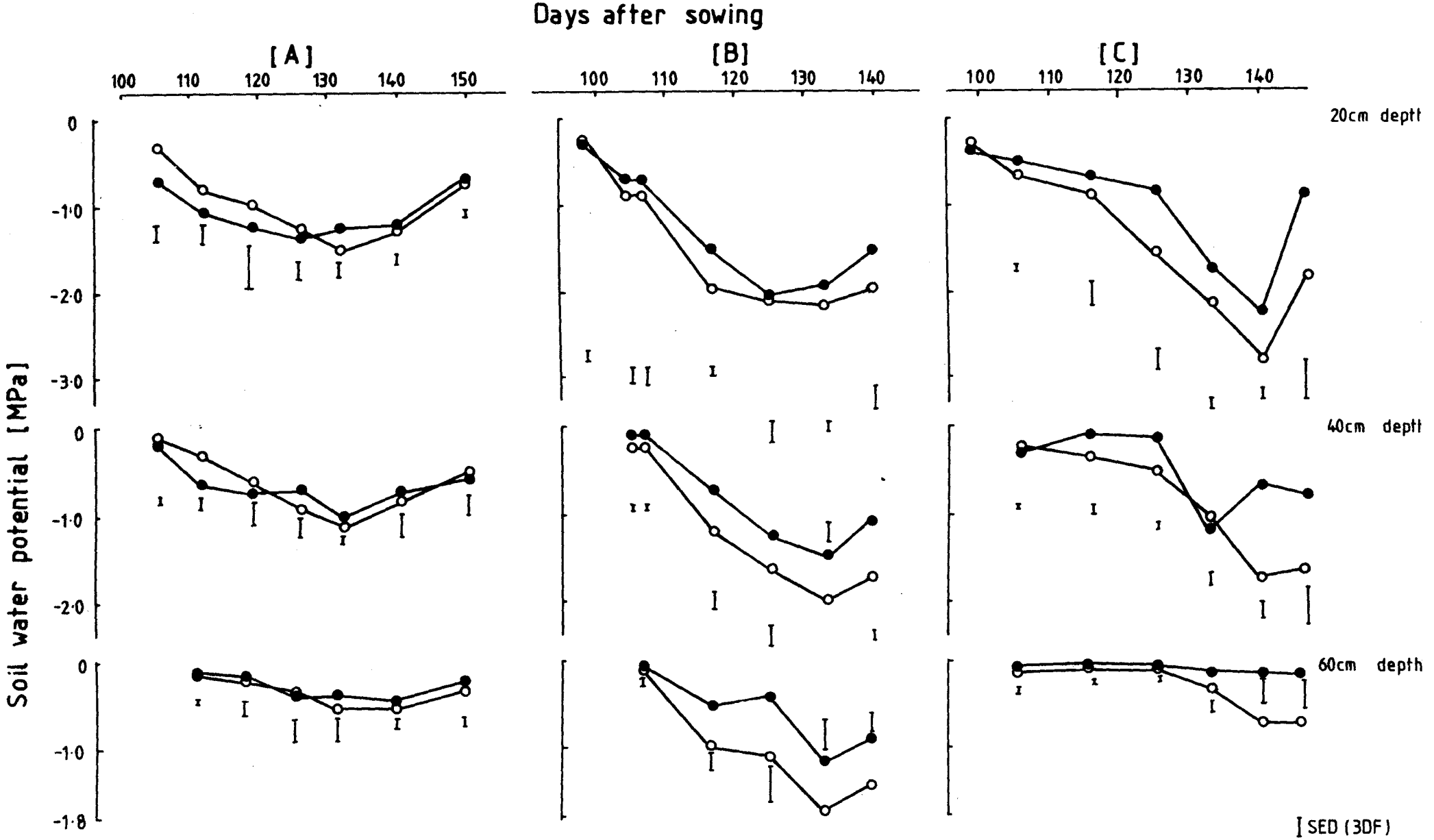
where L is the LAI of the canopy.

The mean ratio of K_i/K_f was calculated for each treatment (Table A.2) and this value was subsituted into equation A.9 for each measurement of F_f found in Table A.1 to give an estimate for the fractional light interception (F_e)

Table A.2 The attenuation of radiation by barley canopies calculated from solarimeter and photographic data

Days after sowing	F_f	F_i	K_f	K_i	K_i/K_f
CONTROL					
52	0.76	0.48	0.76	0.34	0.45
59	0.86	0.58	0.65	0.30	0.46
65	0.87	0.71	0.49	0.29	0.59
COMPACT					
52	0.29	0.14	0.80	0.35	0.44
59	0.37	0.17	0.79	0.31	0.39
65	0.83	0.29	0.77	0.35	0.45

Appendix 6 The effect of soil compaction on the seasonal soil water potential under field beans (A), spring barley (B) and grass (C) crops in 1983.
Control (o); Compact (●)


Days after sowing
[A]
[B]
[C]
100
110
120
130
140
150
Soil water potential [MPa]
0
-1·0
-2·0
-3·0
-1·8
20cm deptt
40cm deptt
60cm depth
SED (3DF)